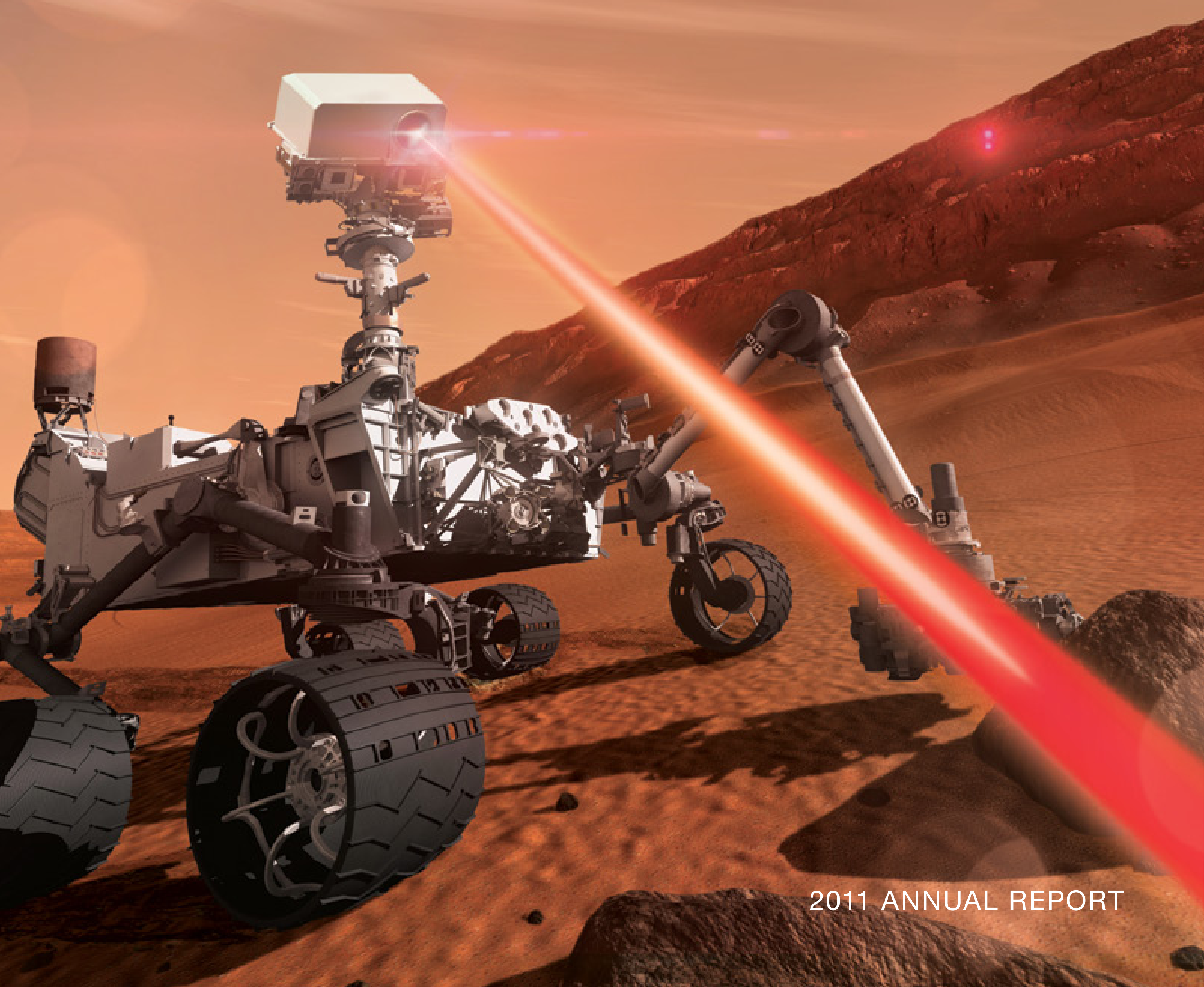
National Aeronautics and Space Administration

Jet Propulsion Laboratory

Microdevices Laboratory

BIG THINGS COME FROM SMALL TECHNOLOGIES



2011 ANNUAL REPORT

Since 1989, MDL has provided end-to-end capabilities in design, fabrication, and characterization of advanced components and sensors. MDL research and development activities have produced seminal contributions to the microdevice technology revolution, and our novel and distinctive products enable remarkable achievements in NASA's space and Earth science programs. In addition, MDL products are used in numerous applications in support of other national priorities.

The work and contributions of the talented MDL scientists, technologists, and research staff hold the promise of further extensions of our ability to peer into the far reaches of our solar system, other galaxies, and the very beginnings of our universe. At Microdevices Laboratory, we believe **Big Things Come From Small Technologies**.

On the cover: NASA-JPL's Curiosity rover with artistic rendition of the ChemCam (Roger Wiens, a LANL/IRAP/JPL collaboration) instrument laser source. Curiosity carries ten science instruments including the Tunable Laser Spectrometer with its interband cascade laser developed at MDL.

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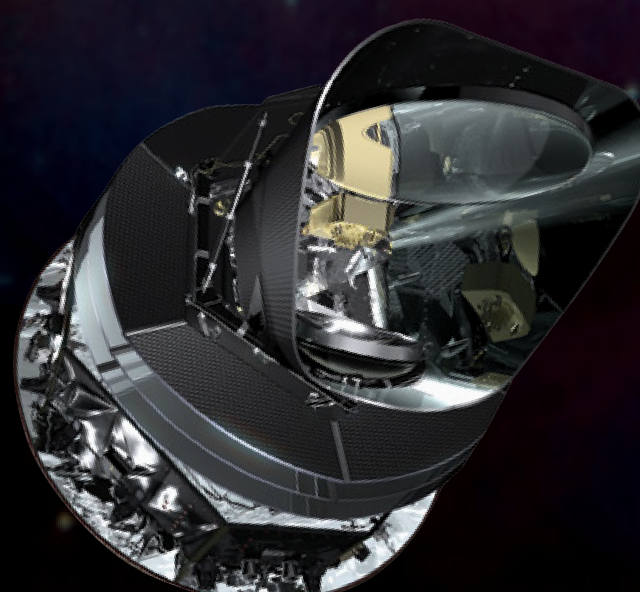
MDL technologies continue to play pivotal roles in current and future NASA missions.

CRISM (Compact Reconnaissance Imaging Spectrometer for Mars)

Two curved gratings fabricated at MDL serve as the dispersive elements for CRISM, an imaging spectrometer that has been flying aboard the Mars Reconnaissance Orbiter since 2005. CRISM seeks to find traces of past and present water on the Martian surface and to map the geology, composition, and layering of surface features.

MIRO (Microwave Instrument on the Rosetta Orbiter)

MIRO's 557-GHz radiometer utilizes subharmonic planar diode mixers and multipliers fabricated in MDL to study gases given off by comets. The European Space Agency's Rosetta Orbiter was launched in March 2004 on a 10-year journey to rendezvous with comet 67 P/Churyumov-Gerasimenko.

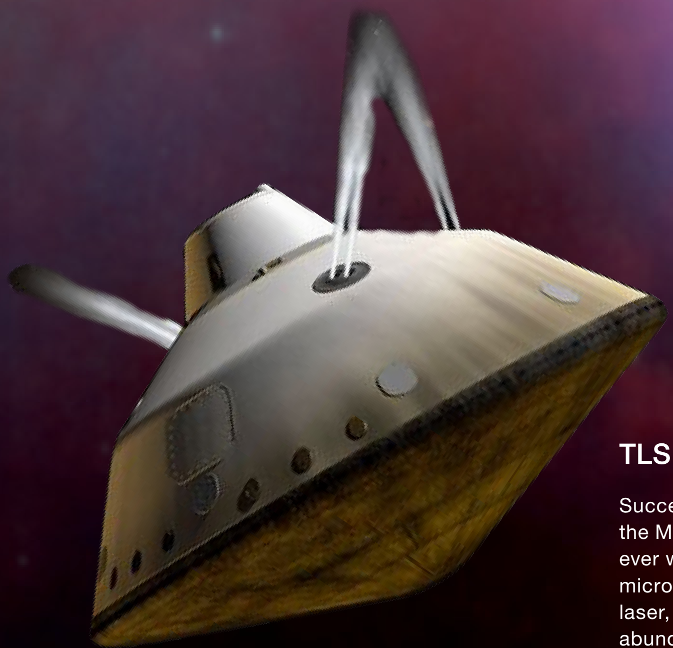


Planck HFI (High Frequency Instrument)

Planck is designed to image the anisotropies of the cosmic background radiation field over the whole sky with unprecedented sensitivity and angular resolution. MDL's HFI is an array of 52 bolometric detectors in the focal plane of the Planck telescope that images the sky at six frequencies between 100 GHz and 857 GHz.

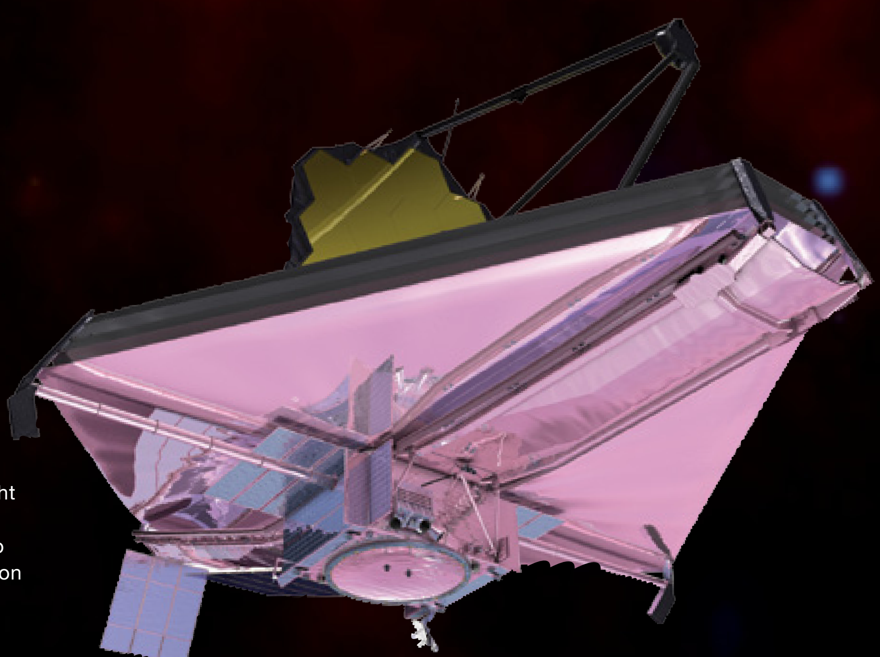
Herschel SPIRE (Spectral and Photometric Imaging Receiver)

The Herschel Space Observatory is the largest infrared space observatory launched to date. Herschel observes at wavelengths that have never previously been explored. SPIRE, one of the three Herschel instruments, employs arrays of spider-web bolometers designed and fabricated at MDL. They are currently the most sensitive detectors available.



TLS (Tunable Laser Spectrometer)

Successfully launched on November 26, 2011, TLS aboard the Mars Science Laboratory will assess whether Mars ever was, or is still today, an environment able to support microbial life. Enabled by the MDL interband cascade laser, TLS is capable of determining atmospheric methane abundance to unprecedented sensitivities.



NIRCam (Near Infrared Camera) Coronagraph

MDL recently completed and delivered five flight occulting masks for the James Webb Space Telescope NIRCam coronagraph. Scheduled to launch in 2018, NIRCam will enable the detection and characterization of orbiting exoplanets.

This spread: Artists' renderings of Mars Reconnaissance Orbiter, Rosetta Orbiter, Planck Space Observatory, Herschel Space Observatory, Mars Science Laboratory, and James Webb Space Telescope.

LETTER FROM THE DIRECTOR

This has been another exciting year for infusion of MDL-developed technologies into projects of national interest for astrophysics, planetary and Earth science, as well as NASA missions, industry, private business, defense, healthcare, and public safety.

Scientists at an October 2011 planetary meeting in France were enthralled by the news that, unlike other comets, comet Hartley 2 had water of the same isotopic composition as that on Earth! This important observation — made by the Herschel Space Observatory using MDL-developed submillimeter devices — provided a tantalizing clue that may unlock the mystery of the origin of water on Earth itself. Primitive bodies like comets and asteroids are yielding their secrets to these submillimeter devices that are identified for possible future exploration of Jupiter's moons Ganymede and Europa, whose icy crusts are thought to protect liquid water interiors that may harbor early life forms.

In the visible-infrared region, our electron-beam-crafted diffraction gratings also provide unprecedented spectral information and have enjoyed a busy year on missions circling three solar system bodies: our own precious planet, studying rainforest canopy health, coastal ecosystems and communities, and volcanic activity, and in fast-response to fire, earthquake, and tsunami events; the Moon, creating high-detail mineralogical maps on board the Indian spacecraft Chandrayaan-1; and orbiting Mars on board the Mars Reconnaissance Orbiter mission to map the mineralogy of the red planet, allowing scientists to understand Mars' watery past and identify Gale Crater as the landing site for JPL's Mars Science Laboratory (MSL) mission.

Now en route to Mars, the MSL mission's "Curiosity" rover carries the tunable laser spectrometer (TLS), which will investigate isotope ratios in carbon, hydrogen, and oxygen to assess present-day habitability and whether Mars ever supported life. TLS includes a new kind of semiconductor laser — the interband cascade laser — developed at MDL specifically for methane detection. If methane is detected at high levels, its carbon-13 isotope ratio will be a powerful discriminator between biological (subsurface bacteria) and nonbiological (rock chemistry) sources. On Earth, methane and carbon dioxide are important greenhouse gases whose measurement from space needs laser sources of unprecedented power and reliability

On November 26, 2011, NASA launched the Mars Science Laboratory. MDL's TLS instrument is a vital component on its "Curiosity" rover.

Artist's rendering of Mars Science Laboratory.

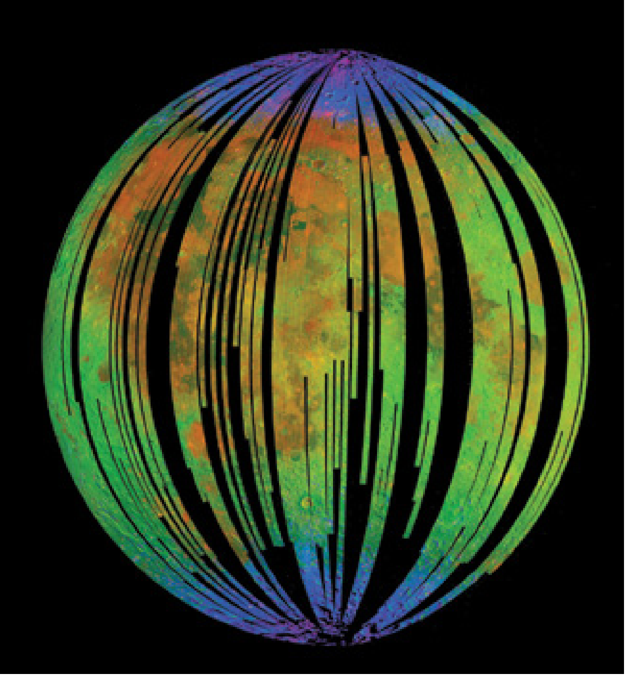
Now en route to Mars, the MSL mission's "Curiosity" rover carries the tunable laser spectrometer (TLS), which will investigate isotope ratios in carbon, hydrogen, and oxygen to assess present-day habitability and whether Mars ever supported life.

for trend analysis of sources and sinks. In anticipation of space-based lidars to provide global data sets, MDL is developing semiconductor lasers between 2 and 5 μm tailored for single-mode injection into high- power transmitters.

Exploration of the Moon took another giant leap forward with MDL-developed microthermopile array detectors that enabled the Diviner instrument on the Lunar Reconnaissance Orbiter to completely map surface temperatures as low as –250 °C in lunar craters and polar regions, and the rock-dust distribution during the recent June 2011 eclipse. On Earth, these thermopile arrays have achieved the ultra-sensitive, wide dynamic range needed for separating solar reflection from Earth-emitted radiation from the top of Earth's atmosphere all the way down to the surface, and will be integrated into NASA's Earth Observing System.

In addition to the e-beam gratings and slits needed for advanced spectrometers, detector technologies are key to providing fast-response, high-sensitivity detection. In the infrared, large-area focal plane arrays based on megapixel arrays of quantum-well infrared photodetectors (QWIPs) and high-temperature barrier infrared detector (BIRD) architectures are shining examples of MDL innovation and excellence provided for NASA, defense, intelligence, and national security. At ultraviolet wavelengths, MDL has focused on improving detector quantum efficiency through delta-doping and developing robust, high-performance optical coatings that together are providing new capability for Earth ionosphere studies, and peering into the interstellar and intergalactic media to reveal clues to the evolution of the universe.

Hydrocarbon clouds, aerosol, and rain would greet any planetary instruments plunging into the frigid (–200 °C) methane lakes of Saturn's moon Titan to search for complex organics thought to be precursors to self-replicating life forms. To analyze cryogenic liquids like methane



A three-color mosaic from the Moon Mineralogy Mapper (M3) on board Chandrayaan-1. Blue indicates the signature of water, green shows the brightness of the surface, and red indicates iron-bearing minerals. M3 utilized a shaped-groove convex diffraction grating designed and fabricated at MDL.

Image courtesy ISRO/NASA/JPL-Caltech/Brown University/USGS.

and ethane thought to comprise the large lakes observed by the Cassini–Huygens mission, MDL is teaming with university and industrial partners to pioneer lab-on-a-chip microfluidic spectrometers with capability for detecting long-chain amines and identifying their molecular chirality or “handedness” — a recognized biosignature. On Earth, highly sensitive, portable microfluidic-based systems are being developed for the analysis of petroleum products and various dirt/soil mixtures to assess toxicity and quantify contamination levels.

MDL continues to develop specialized carbon nanotube structures that can provide highly efficient, directional electron sources with savings in mass, power, and measurement time. These qualities will transform a new generation of X-ray, Raman, and mass spectrometers that retain the sensitivity of larger laboratory-based spectrometers packaged into the small, robust packages needed for planetary probes.

After 30 years in Earth and planetary scientific research, witnessing first-hand how advanced technologies can initiate important scientific discoveries, it is truly an honor and privilege for me to join the MDL family. We take great pride in the pursuit of technical excellence and innovation. With NASA and Caltech, our Chief Technologist Dr. Jonas Zmuidzinas, Deputy Director Dr. Siamak Forouhar and I join our university, industrial, defense and commercial partners in the incredible achievements to date across a diverse range of applications. The next few years will no doubt witness unprecedented growth in innovative, miniaturized technologies of high capability and wide applicability that are our trademark and inspiration.

Dr. Christopher Webster
Director
JPL Microdevices Laboratory

LETTER FROM THE DIVISION MANAGER

The broad capability of MDL continues to play a vital role in instrument development at JPL. MDL is home to many technological innovations central to instruments with unique capabilities that enable new scientific discoveries.

This past year, under the guidance of the MDL Director, Dr. Jonas Zmuidzinas, we continued our investment plan for upgraded capabilities. During FY11, we invested in advancing MDL capabilities in material characterization. Two noteworthy investments are the addition of an X-ray Diffraction (XRD) system and an Electrochemical Capacitance Voltage (ECV) profiler. The XRD system is a fundamental analysis tool that is necessary for any program that involves deposition or growth of materials when the quality or nature of the materials is important for the application. This tool can be used to characterize crystalline materials grown using epitaxial methods as well as amorphous materials. The newly installed ECV profiler allows the measurement of carrier type and concentration vs. sample depth (doping profiles) with 1 nm depth resolution, applicable for III-V and II-VI semiconductors, III-Nitrides, Si, and SiC films.

It has been an exciting year at MDL, with advances in sensors, components, and systems ranging from microwave kinetic inductance detectors (MKIDs) to solar-blind, UV-sensitive focal planes to miniaturized stereo cameras. We expect that these kinds of technologies will be infused into new missions to expand knowledge of our planet, our solar system, and our origins.

Over the past few years, we have enjoyed the leadership of Dr. Zmuidzinas in the role of MDL Director. It is with mixed emotions that we bid him farewell, and wish him success in his new role as the JPL Chief Technologist. At the same time, we are pleased to welcome Dr. Chris Webster as his successor. Dr. Webster has a rich history of collaboration with many technologists who work in the MDL through the development of his TLS instrument — part of the Sample Analysis at Mars instrument suite on Mars Science Laboratory. We look forward to Dr. Webster's leadership as we look for new opportunities to infuse component technologies into systems to enable or enhance new scientific observations.

Dr. Thomas S. Luchik
Manager
Instruments and Science Data Systems Division

The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on board Mars Reconnaissance Orbiter helped identify Gale Crater as the landing site for Mars Science Laboratory. Gale Crater was chosen for its intriguing signature of clay near the bottom of the mountain inside the crater and sulfate minerals a little higher up. Both minerals are formed in the presence of water, which increases the potential for life-friendly environments. MDL provided two electron-beam fabricated convex gratings for CRISM.

Artists' renderings of the Mars Reconnaissance Orbiter and Gale Crater.
Gale Crater artwork courtesy Kees Veenenbos, NASA Data MOLA Science Team.

OPTICAL COMPONENTS

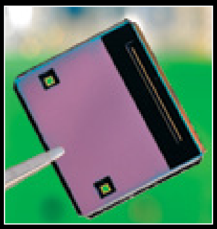
MDL's precision optical devices are at the heart of instruments that realize new capabilities across wavelengths from the ultraviolet to far-infrared.

MDL's Optical Components Group develops electron-beam lithography techniques to fabricate unique optics that enable JPL instruments to perform novel measurements and achieve unmatched performance. Our portfolio of e-beam fabrication processes includes binary nano-patterning of metals, semiconductors, and dielectrics, and analog surface-relief (gray-scale) profiling of polymer resists that can be transfer etched into dielectric and semiconductor substrates. These techniques allow creation of diffractive optics such as halftone coronagraph occulting masks, wire-grid polarizers, semiconductor laser gratings, blazed gratings, microlenses, and computer-generated holograms, for wavelengths from ultraviolet to long-wave infrared. Further, we have developed the capability to electron-beam fabricate these diffractive optics on non-flat (convex or concave) substrates with several millimeters of height variation. >>

MDL Contributes to the Next Generation of Solar-Illuminated Earth Science Missions

JPL's Next Generation Imaging Spectrometer (NGIS) is a pushbroom system that performs high-accuracy imaging spectrometry over the solar-reflected wavelength range 380 to 2500 nm. A single Offner spectrometer design is being used for several airborne instruments: Carnegie Airborne Observatory, National Ecological Observatory Network, and the Next Generation Airborne Visible/Infrared Imaging Spectrometer.

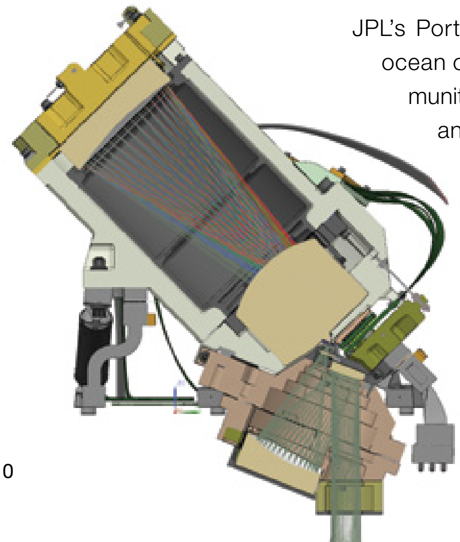
MDL fabricates micromachined slits and the e-beam fabricated gratings for the NGIS spectrometers. The grating for NGIS is a triple-blaze convex grating with the blaze areas arranged as concentric annular zones. The blaze angles and areas are chosen such that the area-weighted spectral efficiency of the first diffraction order equalizes the instrument signal-to-noise ratio when the illumination spectrum and detector spectral responsivity are taken into account. Through 2011, MDL delivered gratings and slits for several NGIS spectrometers that have been successfully assembled and tested.



Right (top to bottom): MDL e-beam fabricated triple-blaze convex grating and micromachined slit for the NGIS spectrometer.

Below: Through the integration of multiple technologies, including one designed and built by JPL, the Carnegie Airborne Observatory can create 3D chemical maps of tropical forests and other ecosystems anywhere in the world. This image shows the chemical and biological diversity of tropical forests imaged for the first time in the western Amazon.

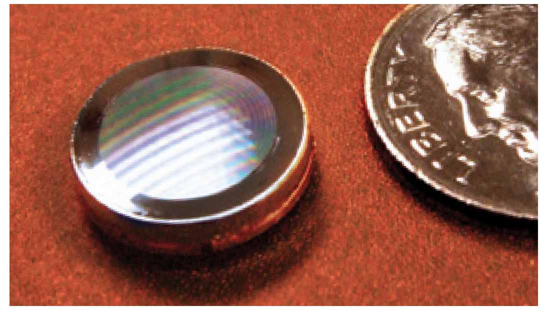
Imaging Spectrometer Designed to Study Coastal Ecosystems and Their Communities in Field Testing Stage



JPL's Portable Remote Imaging Spectrometer (PRISM) is designed to accurately measure ocean color for studying episodic hazards and pollutants in coastal ecosystems and communities. Imaging spectrometry of these regions is difficult due to the low ocean reflectance and unknown atmospheric polarization; hence, the system requires optics having low scatter and low polarization sensitivity. For PRISM, MDL designed and fabricated an optimized shaped-groove grating that exhibits less than 2 percent polarization sensitivity over the wavelength range 350 nm to 1000 nm. The grating is used in a Dyson-relay imaging spectrometer design to achieve very high optical throughput. During the past year, PRISM was fabricated and aligned and is beginning laboratory and field testing.

Left: Illustration of the PRISM optical system.

Ultra-Compact Imaging Spectrometer for Rover-Mounted Operation



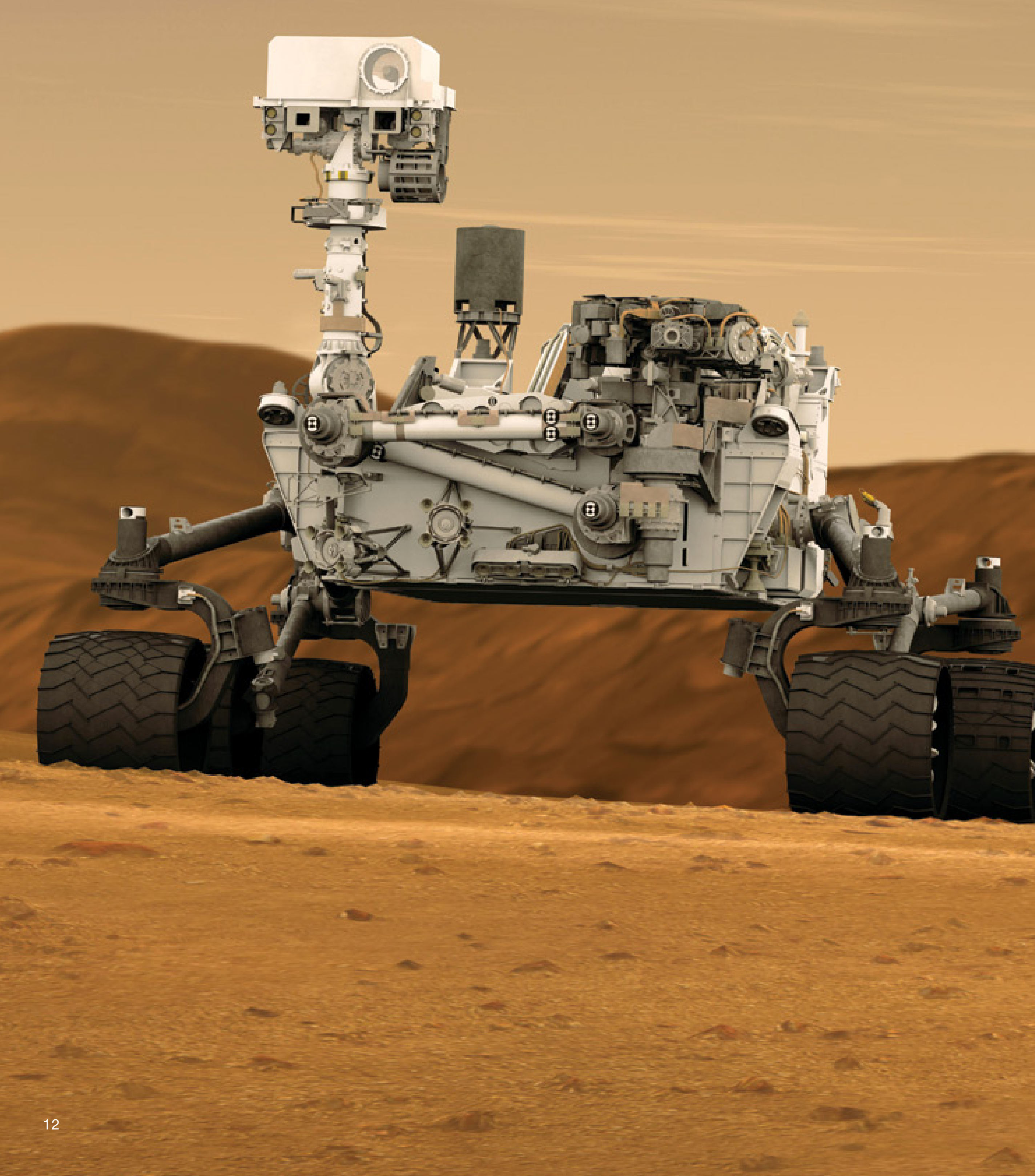
The success of JPL's Moon Mineralogy Mapper (M3) imaging spectrometer for deriving solar-illuminated mineralogical properties has driven interest in miniaturizing such a system for in situ use on other solar system bodies. JPL's Ultra-Compact Imaging Spectrometer (UCIS) is a highly miniaturized M3-like Offner pushbroom spectrometer suitable for a Mars-like rover where it could be mounted on the rover mast for determining the mineralogy of the surrounding terrain and guiding the rover towards closer examination of scientifically important targets. MDL has successfully designed and e-beam fabricated a shaped-groove grating on a very small substrate (~1 cm diameter) that maximizes and spectrally equalizes the overall signal-to-noise ratio of the UCIS instrument. Ultimately, UCIS will achieve a mast-mounted total mass of 1.5 kg, with some additional electronics potentially located on the rover body, enabling high-resolution imaging spectroscopy from a rover platform.

HyTES will be useful for a number of applications, including high-resolution surface temperature and emissivity measurements and volcano observations.

High-Performance Pushbroom Imaging Spectrometer for Thermal Infrared Earth Science

The Hyperspectral Thermal Emission Spectrometer (HyTES) will be the premier airborne thermal imaging spectrometer for Earth science. The HyTES spectrometer is a compact, high-throughput Dyson relay that will provide high-accuracy spectra in the wavelength band from 7.5 to 12 μm. MDL provided three key components for integration into HyTES: a high-efficiency e-beam-fabricated concave grating, an ultra-straight and uniform micromachined slit, and a broadband-response quantum-well infrared photodetector (QWIP) array. HyTES is currently being assembled, aligned, and tested at JPL.

Expected to land in August 2012, the Mars Science Laboratory rover, named “Curiosity,” will assess whether Mars ever was, or is still today, an environment able to support microbial life. The methane, water, and carbon dioxide measurements provided by the tunable laser spectrometer on the Sample Analysis at Mars instrument suite (page 15) will add essential information needed to answer this fundamental question.



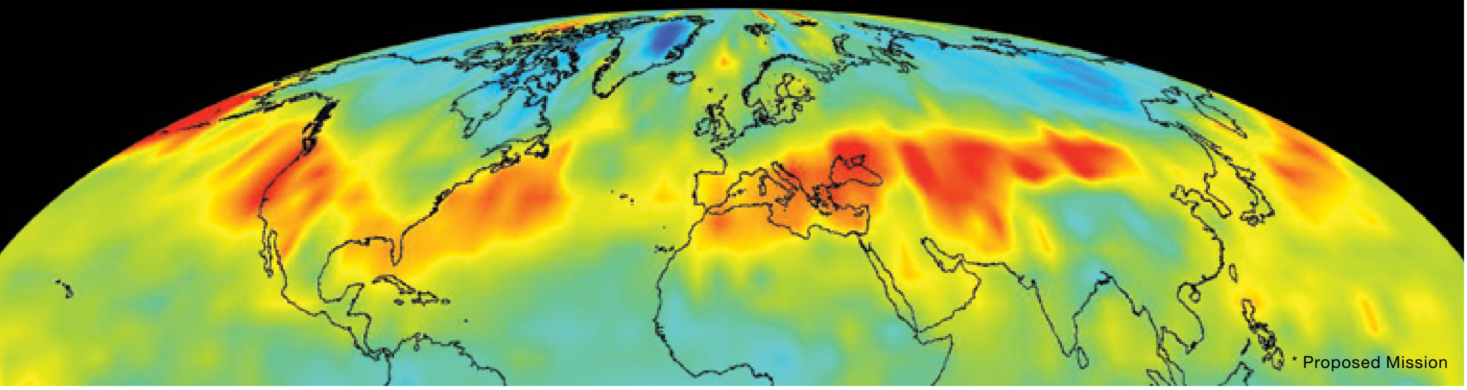
Artist’s rendering of Mars Science Laboratory Curiosity rover.

SEMICONDUCTOR LASERS

MDL instruments capable of precisely measuring the sources and emission rates of carbon dioxide and methane on Earth are on their way to Mars to carry out similar analyses. Next stop: Saturn and its moon Titan.

JPL and NASA have a long history of flying tunable diode laser spectrometers on Earth and planetary missions for atmospheric and trace gas analysis. Most of the semiconductor lasers of interest require unique characteristics that are often unavailable commercially. For this reason, MDL has been involved in the design and fabrication of space-qualified semiconductor lasers since its inception. Two significant accomplishments are the delivery of the first InGaAsP 2.06-μm distributed-feedback semiconductor laser for detection of water and carbon dioxide isotopes to the Mars Volatiles and Climate Surveyor (Mars'98 mission) and the delivery of the first 3.27-μm interband cascade laser for detection of methane and its isotopes. The latter is the heart of the tunable laser spectrometer on Mars Science Laboratory, launched on November 26, 2011. >>

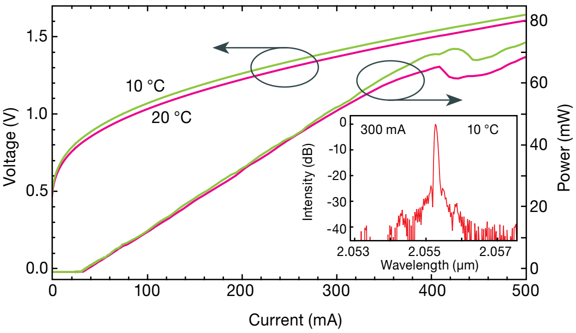
Data from NASA's Aqua satellite show concentrations in the atmosphere of CO_2, a gas known to influence climate change. ASCENDS* would provide continuous global-scale measurements of CO_2.



* Proposed Mission

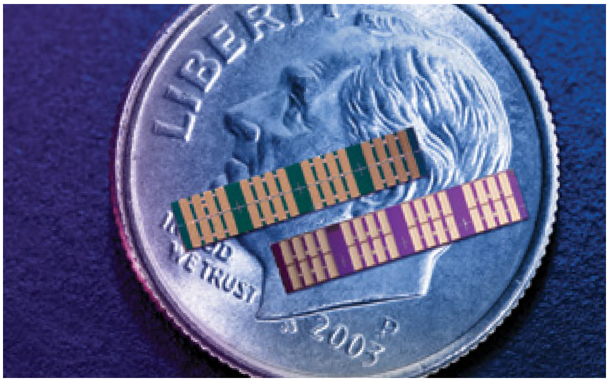
Semiconductor Laser Is Key in Monitoring CO_2 and Other Greenhouse Gases

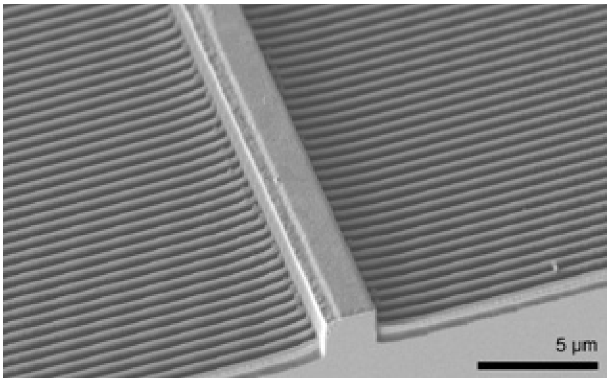
The lack of accurate global-scale observations of CO_2 and other greenhouse gas emissions at Earth's surface represents a major hurdle for improving our understanding of biosphere–atmosphere exchange processes and potential climate effects. Space-based integrated-path differential-absorption (IPDA) lidar has the potential to address this need. NASA is interested in future missions such as ASCENDS (Active Sensing of CO_2 Emissions over Nights, Days, and Seasons) to provide continuous global-scale measurements of CO_2 and other important gases present in Earth's atmosphere.



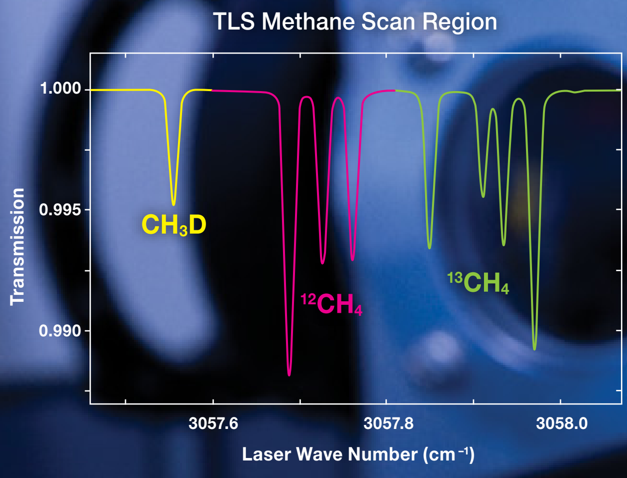
Above: Light-current-voltage characteristics of a laterally coupled DFB laser operating near room temperature. Inset: The single-mode laser emission spectrum at an operating current of 300 mA.

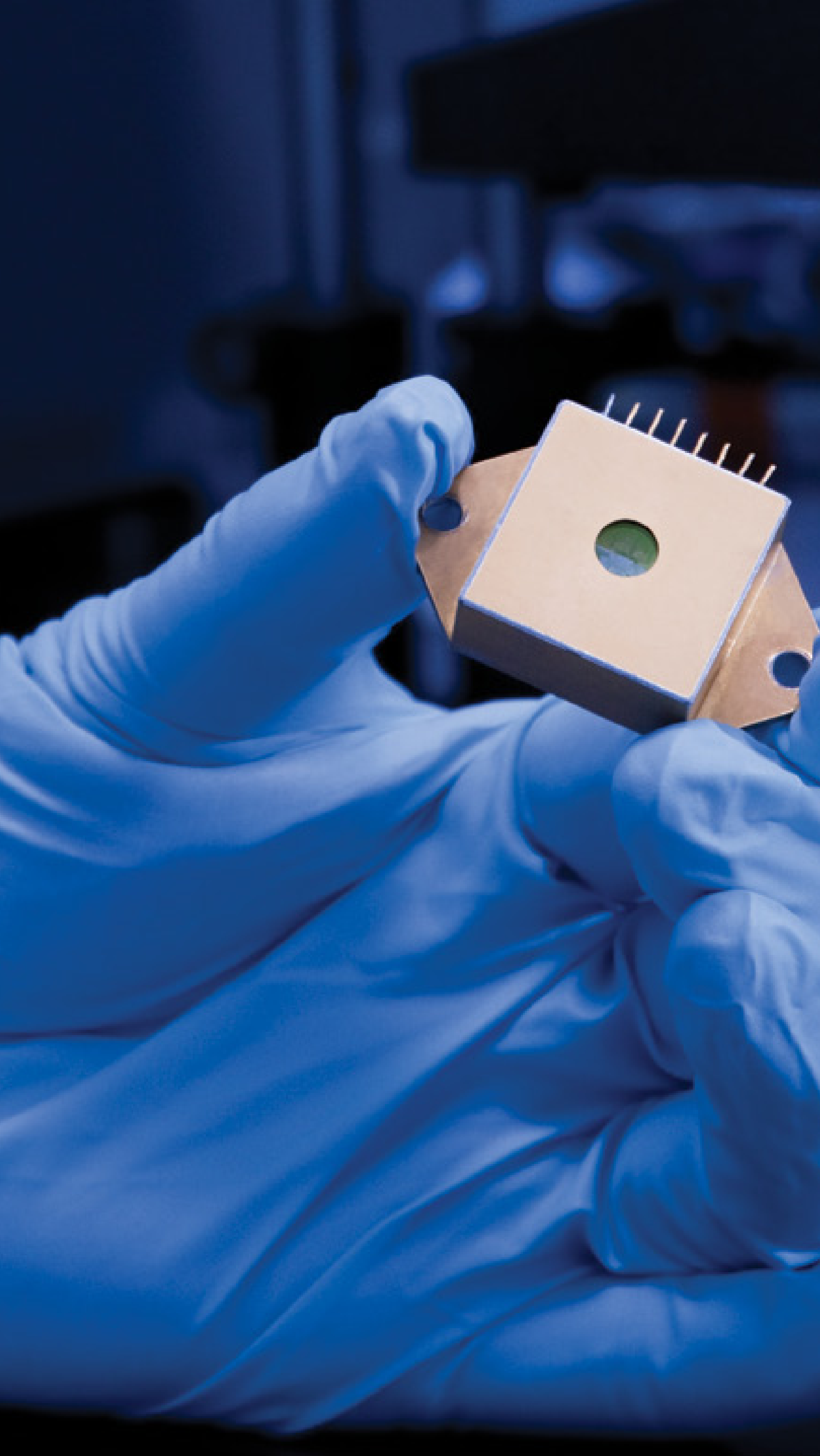
Using lidar for space-based measurements requires laser sources with high efficiency, excellent reliability, and spectral fidelity. The complexity of state-of-the-art solid-state laser transmitters can be substantially reduced by using high-performance semiconductor lasers. At MDL, we are developing distributed-feedback (DFB) semiconductor lasers with unprecedented output power at 2.05-μm wavelength for CO_2 IPDA systems, and lasers at 3.27 μm and 4.6 μm for in situ detection of methane and carbon monoxide.





Above left: Two bars of GaSb-based lasers processed in the MDL cleanroom facility. A single bar consists of 16 individual lasers, each of which is capable of producing more than 50 mW of optical power at 2.05-μm wavelength. Right: Scanning electron micrograph showing the structure of a DFB laser with an etched, laterally coupled diffraction grating.



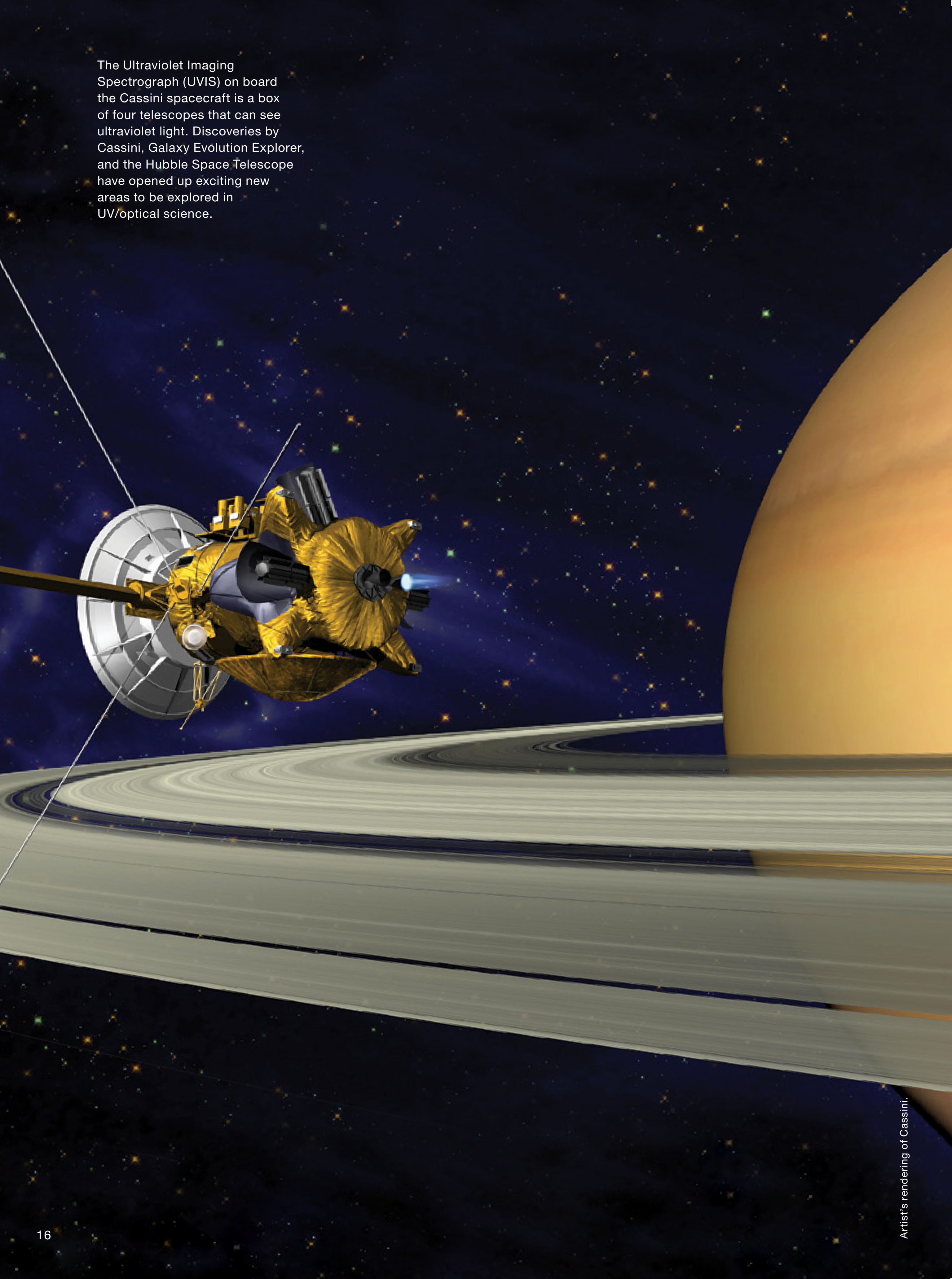


MDL's Tunable Laser Spectrometer Essential to Mars Science Laboratory Mission

The MDL-developed interband cascade semiconductor laser at 3.27-μm wavelength is at the heart of the tunable laser spectrometer (TLS) instrument on board Mars Science Laboratory. It is capable of measuring the abundance of methane and its isotope ratio with very high precision.

Studies of the source and evolution of the Martian atmosphere depend on high-precision measurements of abundances and isotope ratios of atmospheric gases. TLS scans over selected rotational lines within a given vibrational band. Target spectral regions are chosen for strong lines but with minimal spectroscopic interference and comparable temperature dependence important for isotope ratio determinations. Combined with a relatively long pathlength Herriott cell, the high spectral resolution results in high-sensitivity detection with limits at the parts-per-billion level.

The Ultraviolet Imaging Spectrograph (UVIS) on board the Cassini spacecraft is a box of four telescopes that can see ultraviolet light. Discoveries by Cassini, Galaxy Evolution Explorer, and the Hubble Space Telescope have opened up exciting new areas to be explored in UV/optical science.



Artist's rendering of Cassini.

ADVANCED VISIBLE AND ULTRAVIOLET DETECTORS AND IMAGING SYSTEMS

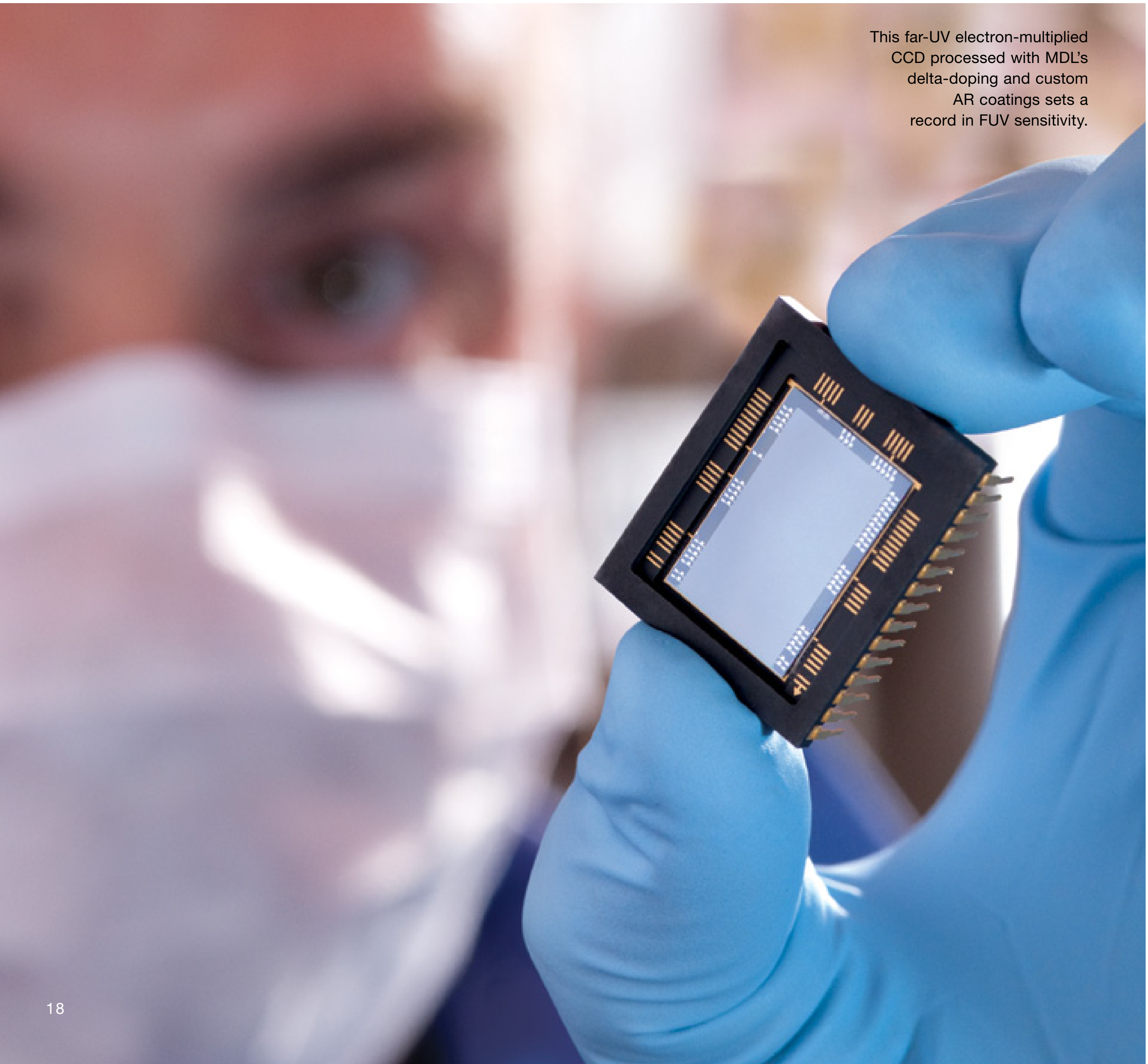
Advances generated at MDL will extend our vision to unprecedented sensitivity of low light levels that will enable unimagined future discoveries and capability.

The Advanced UV, Visible, NIR Imagers, Detectors, and Systems Group develops high-performance ultraviolet/visible/near-infrared imagers, cameras, and camera systems. We specialize in advanced materials for devices, epitaxial growth, atomic layer deposition technologies for surface and interface bandstructure engineering, quantum-dot-based devices, new detector concepts, and nanoscale science. In 2011, achievements included producing deep-ultraviolet imagers by delta-doping 8-inch-diameter CMOS wafers, delivering devices key to suborbital missions, leading a study on next-generation UV instrument technologies, setting a world record in achieving the highest quantum efficiency in the entire UV range, advancing UV/visible photon counting detection solid-state arrays, and enhancing solar-blind UV detection with III-Nitride materials and devices. >>

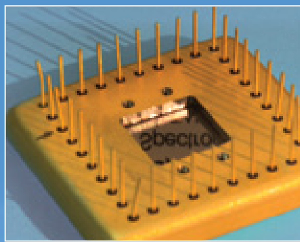
High-Performance, Cost-Effective Silicon Detectors and Imaging Arrays with 8-inch Silicon Molecular Beam Epitaxy

JPL's delta-doping technology uses molecular-beam epitaxy (MBE) with its precision atomic control to modify back-illuminated silicon imagers and enable 100 percent internal quantum efficiency and extended spectral response, as well as stability and uniformity required for precision photometry, high-resolution imaging, and spectrometry applications. JPL's large-wafer capacity with multiwafer capability provides high throughput processing required for producing cost-effective, high-performance detector arrays for instruments. Applications for future missions include a large-aperture UV/optical telescope for cosmology and astrophysics studies, UV spectrometers to map the intergalactic medium (IGM), study planetary atmospheres, and for mineralogy and life detection.

Examples of various devices produced include delta-doped and antireflection-coated (AR-coated) electron-multiplied CCDs (EMCCDs) for future cosmology and primitive body studies that would need single-photon counting capabilities; delta-doped hybrid CMOS imaging arrays for an ultracompact, high-resolution camera for planetary down-hole instruments; deep-UV CMOS imagers with fast readout, and monolithic CMOS and CCD devices for imaging and spectroscopy instruments.



This far-UV electron-multiplied CCD processed with MDL's delta-doping and custom AR coatings sets a record in FUV sensitivity.



Left: A delta-doped low-energy electron detector was delivered for the LEES instrument on board the MICA sounding rocket.

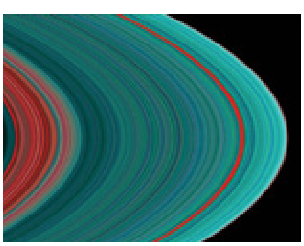
Below: MDL's UV detectors are baselined for the Faint Intergalactic-medium Redshifted Emission Balloon (FIREBALL) scheduled to launch in 2014.

MDL Technologies Support Suborbital Flight Missions

In 2011, MDL delivered two detectors for suborbital flight missions. One delta-doped low-energy electron detector was delivered to the Southwest Research Institute for the Low-Energy Electron Spectrometer (LEES). By improving the detection threshold and removing the need for massive power supplies, MDL enabled a more capable and compact instrument. LEES, expected to launch in 2012 on MICA (Magnetosphere–Ionosphere Coupling in the Alfvén Resonator), will measure low-energy electrons at low altitude to better understand their role in the aurorae precipitation.

A 10-megapixel UV detector for the University of Colorado's Colorado High-Resolution Echelle Stellar Spectrograph (CHESS) rocket was also delivered in 2011. This solid-state detector provides high sensitivity in the UV and removes the need for microchannel plates and high-voltage power supplies.

MDL's UV detectors are now baselined for FIREBALL, a Caltech mission to discover and map faint emission from the IGM.



Saturn's rings, as seen in this ultraviolet image taken with UVIS on board Cassini, show there is more ice toward the outer part of the rings than the inner part. Ultraviolet is interesting because it includes the light characteristics of some key chemical elements and compounds. These light patterns allow scientists to identify conclusively the composition of distant objects.

MDL Selected to Lead Study on Next-Generation UV Instrument Technologies

Discoveries by missions such as Cassini, Galaxy Evolution Explorer, and the Hubble Space Telescope have opened up exciting new areas to be explored in UV/optical science. For discoveries beyond these missions, advances in technology must occur. That need spurred the Keck Institute for Space Studies to select JPL, Caltech, and Columbia University to create new concepts for next-generation UV instruments. Ultraviolet offers one of the few remaining areas of the electromagnetic spectrum where it is possible to create new opportunities for discovery by combining improvements in detector quantum efficiency (5–10 times), optical coatings, and higher-performance wide-field spectrometers (5–10 times), and increasing multiplex advantage (100–1000 times). Innovations in nanostructured materials, detectors, and optics could enable UV instruments with unprecedented performance in throughput, sensitivity, and resolution, as well as significant reductions in mass, power, and cost. Many new concepts were evaluated and prioritized as a result of this study.

MDL's two-color megapixel QWIP FPA (page 22) is integral to the HyTES instrument. HyTES would be useful for a number of applications including the determination of optimal band locations for the thermal infrared instrument on the proposed Decadal Hyperspectral Infrared Imager mission (pictured). This mission concept, currently under consideration, would study the world's ecosystems and provide critical information on natural disasters.

Artist's concept of the Hyperspectral Infrared Imager mission.
Pre-decisional – for Planning and Discussion Purposes Only.

INFRARED PHOTONICS

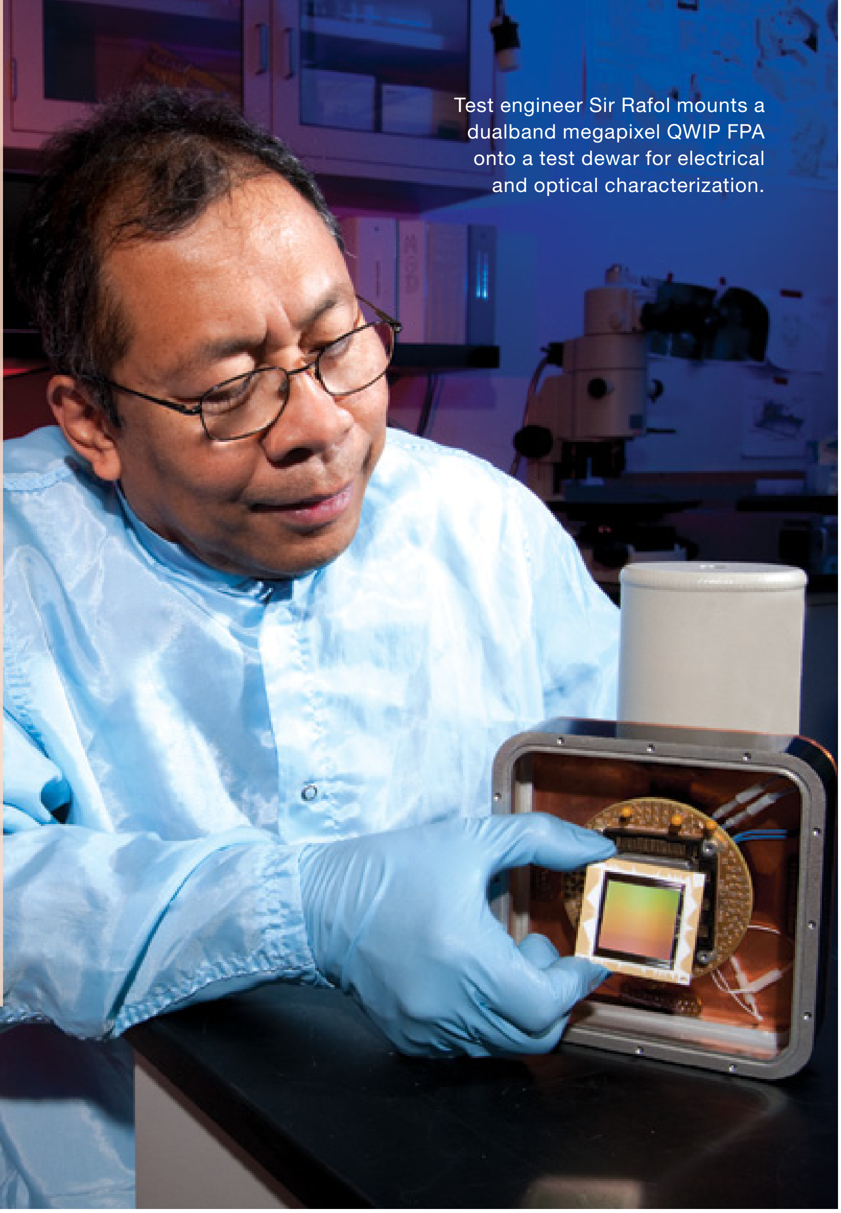
Innovations at MDL enable observations of our planet in an infrared region just beyond our reach, mapping of the world's ecosystems, cloud structures, and natural disasters, and advanced capabilities in medicine and defense.

The Infrared Photonics Technology Group develops infrared technologies based on III-V compound semiconductor hetero-structures. The group is working on four types of infrared detectors based on III-V compound semiconductors such as III–arsenides, III–phosphides, and III–anti-monides. III-V compound semiconductors are based on strong covalent bonds and are much harder than their infrared coun-terpart, II-VI compound semiconductors, which are more ionic and softer. As a result, III-V compound semiconductors are available in up to 8-inch wafers and are easier to grow and to process into large-area arrays. >>

Novel Infrared Focal Plane Array Deliveries

In 2011, we delivered a two-color megapixel quantum-well infrared photodetector (QWIP) focal plane array (FPA) to the Hyperspectral Thermal Emission Spectrometer (HyTES) instrument, funded by the NASA Instrument Incubator Program. This novel two-color FPA consists of eight different progressively changing gratings monolithically integrated to optimize the light coupling into the QWIP pixels receiving light at different frequencies from the spectrometer.

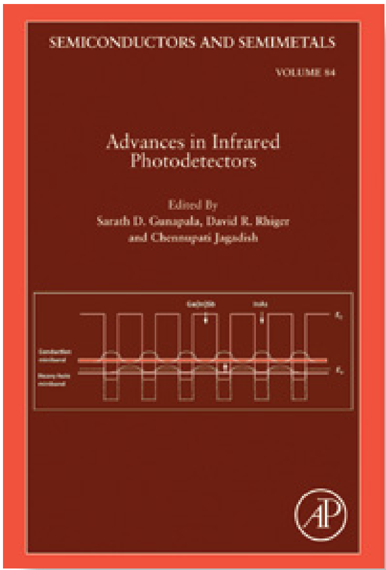
We also delivered a 320x256 and 640x512 pixel first high-operating-temperature (HOT) mid-wave infrared (MWIR) barrier infrared detector (BIRD) FPA, as well as a video graphics array (VGA) format HOT MWIR BIRD FPA, to the U.S. Army. These unique infrared FPAs were all designed and fabricated using MDL's state-of-the-art equipment.



Test engineer Sir Rafol mounts a dualband megapixel QWIP FPA onto a test dewar for electrical and optical characterization.

Comprehensive New Book On Advances in Infrared Photodetectors

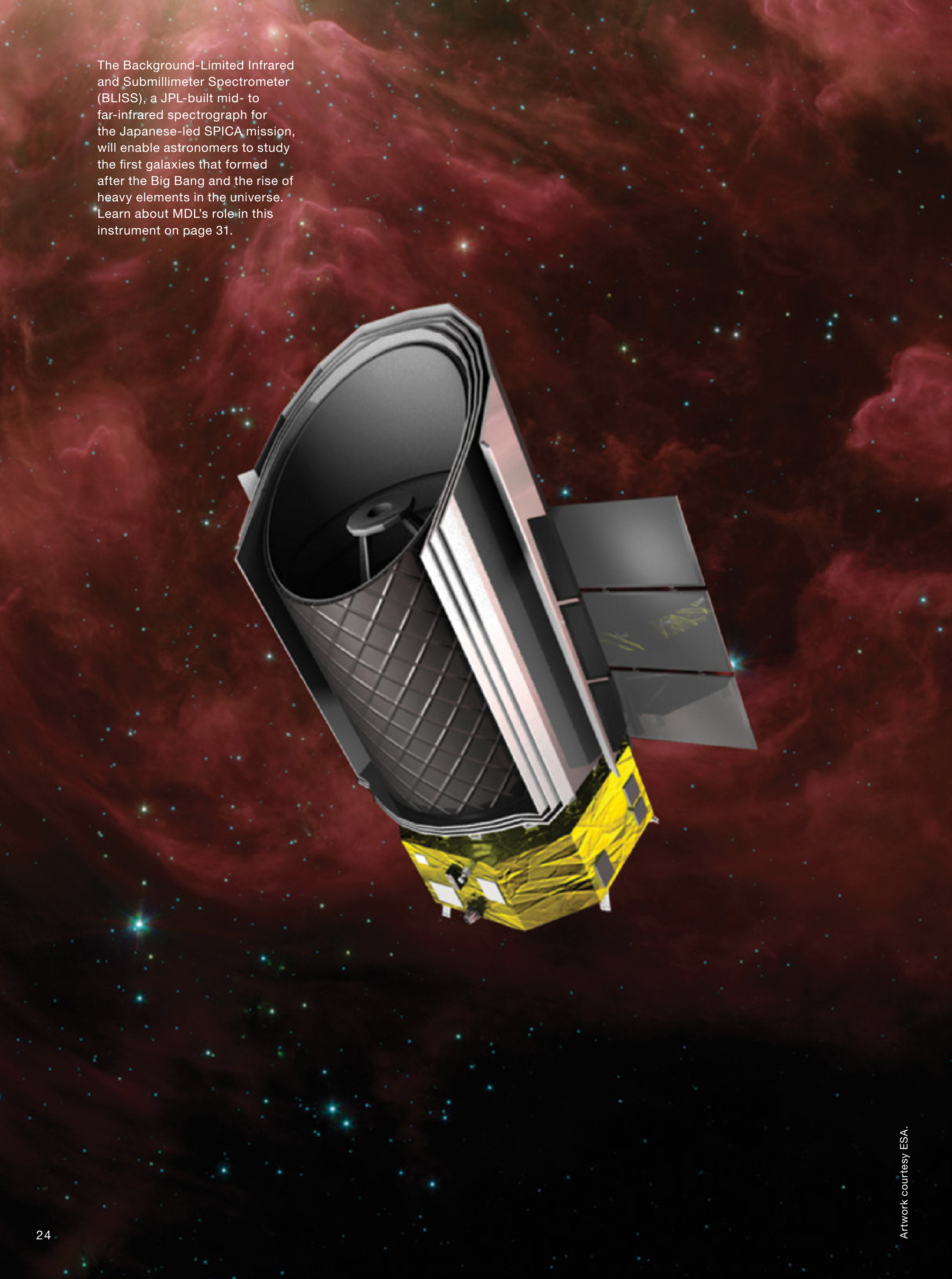
Research in infrared photon detectors has led to many new infrared detection devices, materials, and large-format infrared focal plane arrays for imaging applications. Research efforts in HgCdTe, strained-layer superlattices, quantum-well infrared detectors, homo- and heterojunction devices, quantum-dot infrared detectors, and quantum wells for far-infrared detection have been very intense over last two decades. Sarath Gunapala et al. have collected a comprehensive review of the various topics related to the infrared photon detectors based on II–VI and III–V compound semiconductor materials. We hope that this volume will provide a valuable reference for researchers in infrared detectors and related fields, and for individuals like graduate students, scientists, and engineers who are interested in learning about these subjects. Many members of the Infrared Photonics Technology Group made significant contributions to volume 84 of the book series *Semiconductors and Semimetals*. A significant portion of the work reported in this book was done at JPL's MDL.



NASA Selects JPL to Develop Advanced Infrared Sensors for Space

NASA's Office of the Chief Technologist has selected JPL's MDL to design and fabricate advanced infrared detector technologies in materials, device structures, and focal plane array fabrication. The High Operating Temperature Infrared Sensor Demonstration will use advanced compound semiconductor materials to develop new technologies that may be applied to many future NASA Earth and planetary science instruments and will be used for defense and other applications. The overall goal of this particular technology development effort is to achieve one order of magnitude mass savings and a 100 percent cost savings as compared with traditional cryogenically cooled infrared sensors. The weight and volume savings allow for more compact instruments, which is important when considering payload size and cost. This state-of-the-art technology is truly game-changing and will have spinoff applications for multiple stakeholders in the instrument community.

MDL's John Liu prepares for the focal plane array hybridization process.



The Background-Limited Infrared and Submillimeter Spectrometer (BLISS), a JPL-built mid- to far-infrared spectrograph for the Japanese-led SPICA mission, will enable astronomers to study the first galaxies that formed after the Big Bang and the rise of heavy elements in the universe. Learn about MDL's role in this instrument on page 31.

Artwork courtesy ESA.

SUPERCONDUCTING MATERIALS AND DEVICES

Scientists continue development of devices that detect the cosmic microwave background and the elemental composition of distant galaxies during the formation of the universe, and at home map Earth's radiation balance and empower our new telescopes.

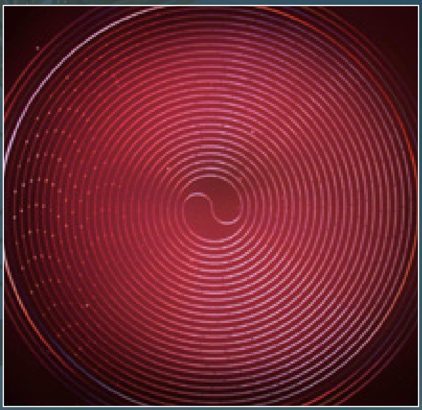
The Superconducting Materials and Devices Group's primary focus is on cryogenic millimeter and submillimeter detectors for spectroscopy, imaging, and polarimetry measurements in astrophysics. JPL has been a pioneer in the development of superconducting detectors for far-infrared/submillimeter astrophysics for 25 years. Initially, this effort focused on superconductor-insulator-superconductor mixers for heterodyne receivers for high-resolution spectroscopy, used on ground-based telescopes around the world as well as on current and planned NASA flight missions. Recent development efforts have been on large-format arrays of direct detectors for spectroscopy, imaging, and polarimetry for astrophysics and application of these technologies for Earth and planetary science. >>

MDL initiated a collaboration with the Owens Valley Radio Observatory in 2011 to investigate whether its new amplifier could greatly improve current state-of-the-art heterodyne receiver systems.

MDL Efforts Improve Heterodyne Receiver Systems

A breakthrough in microwave frequency amplification was made at JPL with the demonstration of broadband gain with a superconducting parametric amplifier capable of reaching quantum-limited sensitivity. During the past year, an average gain of 10 dB was achieved, extending over 2 GHz on either side of a 11.5-GHz pump tone. This bandwidth is a two-orders-of-magnitude improvement over state-of-the-art parametric amplifiers based on Josephson junctions.

Applications of the amplifier include the readout of microwave kinetic inductance detector (MKID) and transition-edge sensor (TES) detector arrays. In addition, the physics of the device allows for operation at much higher frequency, potentially up to 1 THz. By providing a low-noise gain element at millimeter and submillimeter wavelengths, the new amplifier could greatly improve the state of the art of heterodyne receiver systems for these bands.



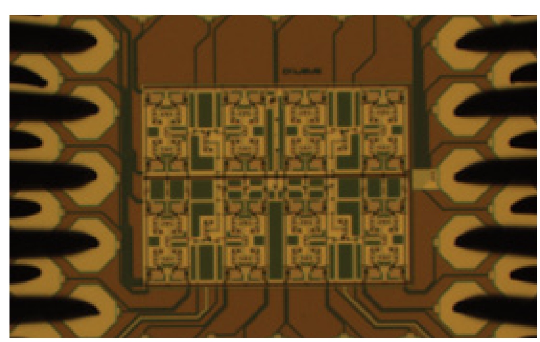
Above: The traveling-wave kinetic inductance parametric amplifier consists of a 1-meter section of NbTiN coplanar waveguide transmission line, compactly arranged in a double spiral. The nonlinearity of the line allows a weak signal tone to draw power from a strong pump tone, producing gain.

The Keck focal plane consists of four 64-pixel dual polarization arrays. Each pixel absorbs incident infrared radiation with a microwave slot antenna and transfers this radiation via a superconducting transmission line to a TES located on a suspended Si-N membrane.

Cosmic Microwave Background Detection

Sustaining its leading role in superconducting TES array technology, MDL developed and continues to improve a process to create arrays of thousands of TESs with high yield (>90 percent). These arrays are being employed on three major astro physics projects, all with the same goal: generating detailed maps of the polarization of the cosmic microwave background (CMB). Building on the success of the 2009 TES focal plane array delivery for BICEP2 (Background Imaging of Cosmological Extragalactic Polarization 2), a ground-based South Pole CMB polarimeter telescope, MDL completed the final two of five focal planes for the Keck array 2012 observation season (a CMB polarimeter experiment that is five times larger than BICEP2). The final of the three missions that will host MDL's CMB focal plane arrays is Spider, a high-altitude, balloon-borne CMB instrument providing a higher sensitivity to the CMB signal by eliminating much of the atmospheric interaction. Two of the six focal planes for Spider's initial launch were completed in 2011, with four more to be completed prior to its deployment in late 2012.

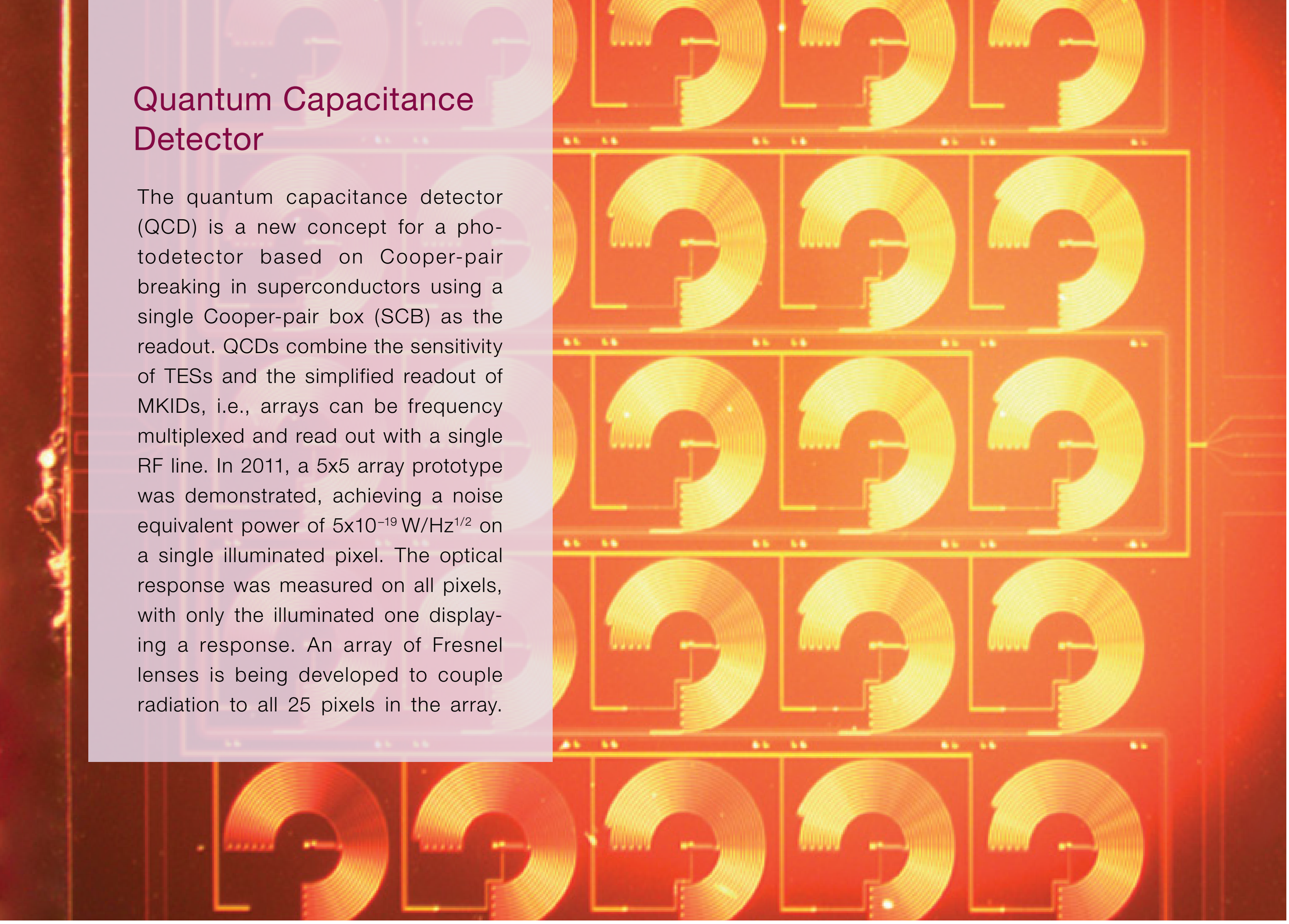
MDL's Superconducting Integrated Circuit Development Advances Quantum Computation



MDL continues to leverage its decades of experience with superconductor sensors to by teaming with D-Wave Systems, Inc., to advance adiabatic quantum computation. A new contract started in June 2011 extends the successful collaboration between D-Wave and JPL, which began in May 2004, through September 2014.

D-Wave has achieved impressive results in mapping combinatorial optimization problems onto two-dimensional arrays of superconducting quantum interference devices (SQUIDs) and exploiting quantum effects to achieve dramatic speedup of calculations and improvement of solution accuracy. On October 28, 2011, D-Wave delivered its first commercial quantum computer to Lockheed Martin.

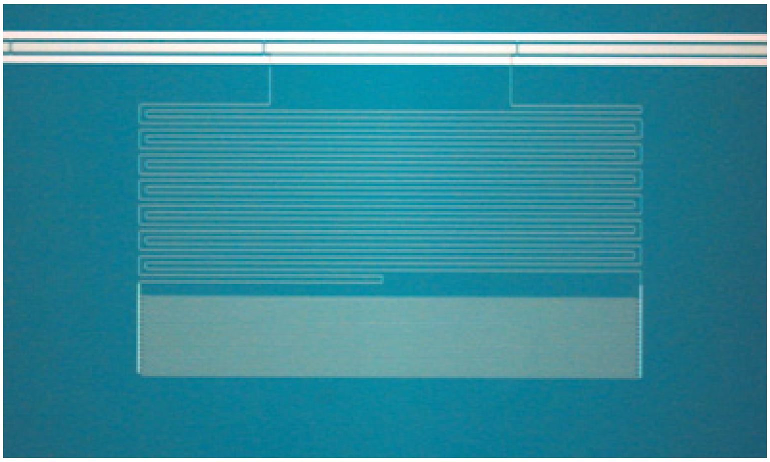
Over the past three years, D-Wave has developed a state-of-the-art manufacturing capability and JPL has transitioned to a research and development role, attacking problems related to decoherence, power reduction, and device physics, prototyping new circuit concepts, and supporting and advancing the D-Wave fabrication process.



Quantum Capacitance Detector

The quantum capacitance detector (QCD) is a new concept for a photodetector based on Cooper-pair breaking in superconductors using a single Cooper-pair box (SCB) as the readout. QCDs combine the sensitivity of TESs and the simplified readout of MKIDs, i.e., arrays can be frequency multiplexed and read out with a single RF line. In 2011, a 5x5 array prototype was demonstrated, achieving a noise equivalent power of 5×10^{-19} W/Hz$^{1/2}$ on a single illuminated pixel. The optical response was measured on all pixels, with only the illuminated one displaying a response. An array of Fresnel lenses is being developed to couple radiation to all 25 pixels in the array.

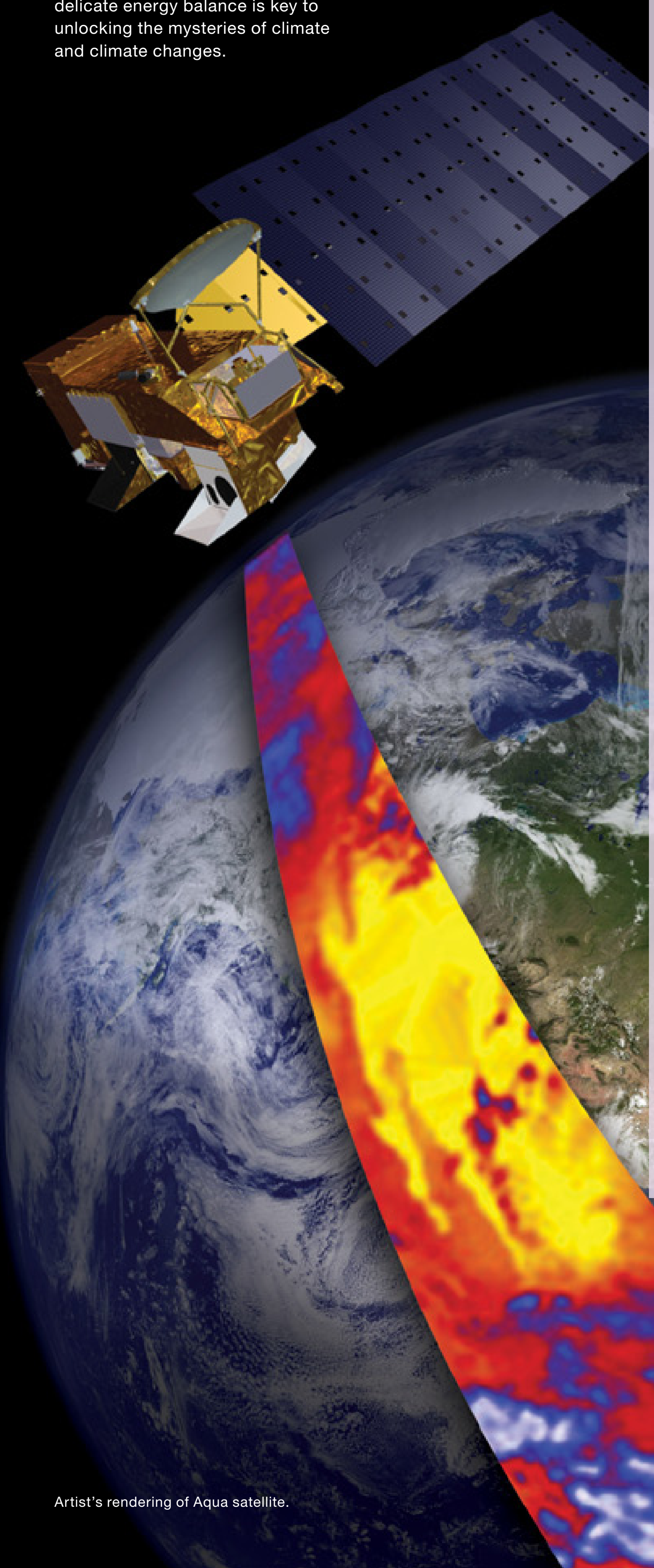
Research on Low-Frequency Kinetic Inductance Detectors



Low-frequency KID resonator consisting of a superconducting NbTiN meandered inductor (top) and an interdigitated capacitor (bottom) coupled to a coplanar waveguide feedline (running across the top).

In 2011, MDL began studying the operation of kinetic inductance detectors (KIDs) at lower readout frequencies. In our previous work, KIDs were read out by frequency multiplexing in the microwave regime (GHz). MDL is now exploring the operation of MKIDs at lower frequencies (tens to hundreds of MHz). There are several advantages to operating KIDs at lower frequency. A major advantage is that the increase in fractional bandwidth of the readout system increases the multiplexing factor significantly. The absolute bandwidth of our current high-speed electronics translates to a higher fractional bandwidth at lower frequencies and enables more resonators of the same quality factor to be packed into the available bandwidth. Additionally, at lower readout frequencies, the contribution of two-level system noise is less important, leading to an improvement in detector sensitivity. This work may enable the development of higher pixel count arrays, which are more cost-effective than those operating at higher frequencies. In 2011, we fabricated test devices to demonstrate the characteristics of low-frequency readout devices (see figure above).

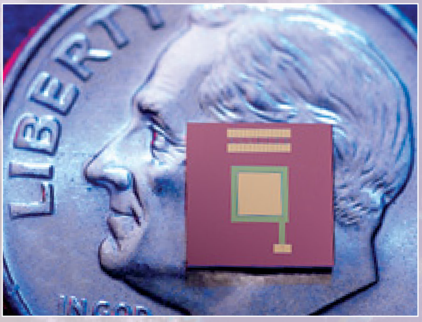
CERES, currently on board NASA's Aqua satellite, detects the amount of outgoing heat and reflected sunlight leaving Earth. Understanding this delicate energy balance is key to unlocking the mysteries of climate and climate changes.



Artist's rendering of Aqua satellite.

Next-Generation CERES Instrument Will Enhance Climate Forecasts

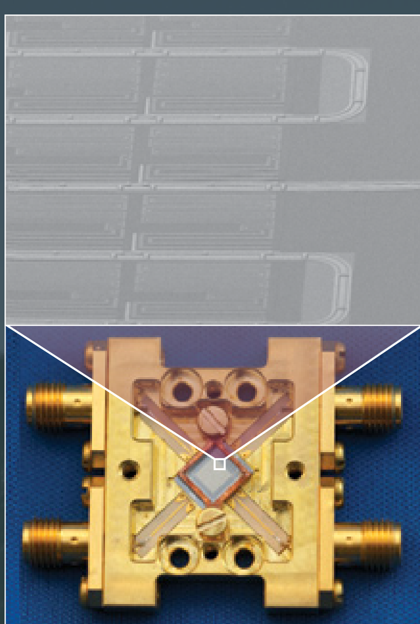
MDL is furthering development of the next-generation CERES-C, a continuation of the Earth Radiation Budget Experiment/Clouds and the Earth's Radiant Energy System (ERBE/CERES) climatological experiment, to measure both solar-reflected and Earth-emitted radiation from the top of the atmosphere to Earth's surface. CERES-C requires detectors that are broadband (absorptivity >90 percent between 0.3–50 μm) with an absorber area of 1.5x1.5 mm, a baseline noise equivalent power (NEP) below 7×10^{-9} W (goal: 2×10^{-9} W) between 0.3–30 Hz bandwidth, a response time between 8–9 ms, a responsivity of at least 65 V/W, and a dynamic range of 0–60 μW. We recently completed a wafer of thermopile detectors and demonstrated that the detectors exceed all the requirements of CERES-C.



Above: The prototype CERES detectors consist of a large, thermally isolated silicon nitride membrane surrounded by roughly 1000 thermocouples. These thermocouples are composed of Bi-Sb-Te compounds and are the key to the high performance of the detector.

First Light at Palomar Using Optical Lumped Element MKID Detectors Made at MDL

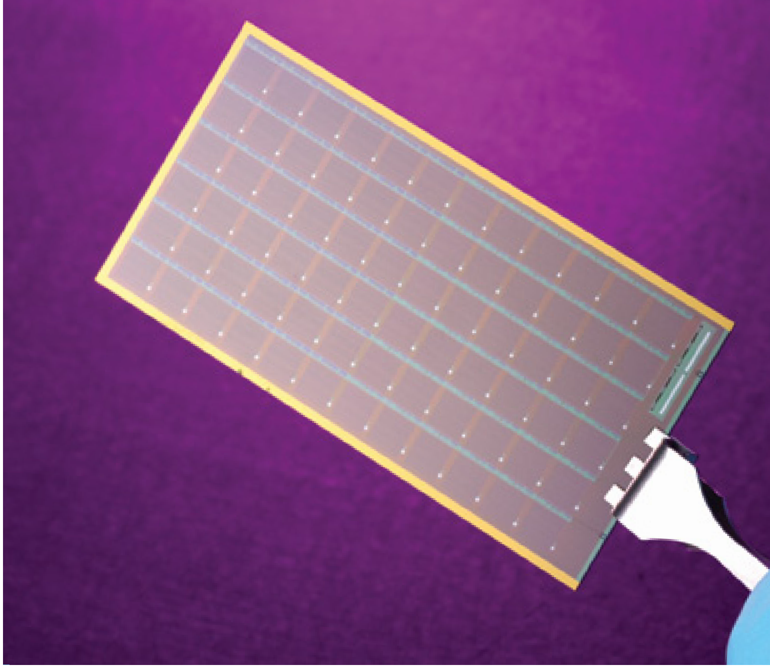
MDL is teaming with Caltech and UC Santa Barbara to develop ultraviolet, optical, and near-IR focal plane arrays based on optical lumped element (OLE) MKIDs. The past year has seen dramatic improvements in the OLE MKIDs. We have gone from single-pixel detectors to 1024 (32x32) pixel arrays with microlenses. Significant work was done to make the arrays uniform enough for science observations. We have demonstrated an energy resolution R=E / E=16. ARCONS (Array Camera for Optical to Near-Infrared Spectrophotometer) was successfully commissioned at the Coudé focus of the Palomar 200-inch telescope on July 28, 2011.



Above (top): Scanning electron microscope image of OLE MKID showing 10 of 1024 pixels and the microwave readout line. Each pixel is on a 100-mm pitch and has a 0.5-mm resonator line spacing.

(Bottom) Microwave coupler block with 1024-pixel OLE MKID array chip mounted with microlens cover.

Focal plane tile containing 6x12x4 color pixels. The microwave feeds come in from the left on this tile. Tiles of this type will be assembled into the focal plane unit so that the microwave feeds will come out on the left for the left bank and the right for the right bank.



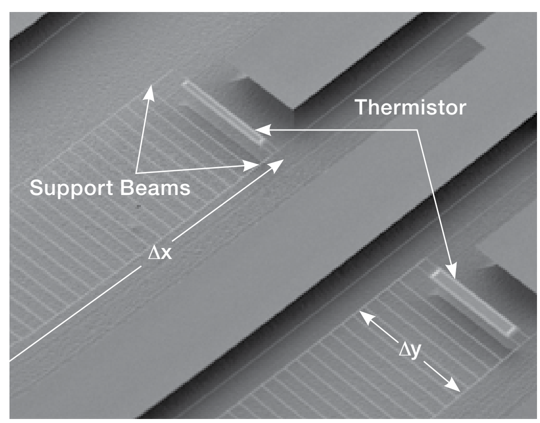
MUSIC Consortium

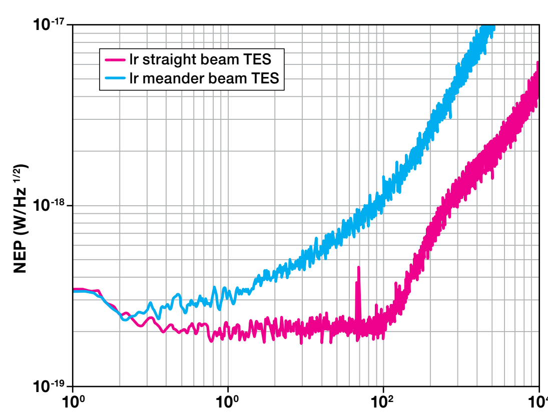
MUSIC (Multicolor Submillimeter Kinetic Inductance Camera) is a camera being developed by a JPL/Caltech/University of Colorado consortium for deployment on the Caltech Submillimeter Observatory. The focal plane is composed of eight identical sensor tiles consisting of 6x12 pixels arrays, each simultaneously observing in four bands. In 2011, MDL finalized the focal plane array tile design and fabricated the first run of devices (left). Array fabrication for the full focal plane took place in the MDL in fall 2011; MUSIC is scheduled for deployment in early 2012.

MDL Demonstrates Ultra-Low-Noise Detectors for BLISS

The Background-Limited Infrared Submillimeter Spectrograph (BLISS) for the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is an ultra-sensitive, broadband grating spectrometer for spaceborne measurements with a resolving power of R~500 and waveband coverage of 35 μm to 435 μm. The superconducting TESs in this instrument operate at T_c=65 mK with a time-domain SQUID multiplexer readout (MUX) to achieve NEP below 10^{-19} W/Hz$^{1/2}$. For noise reduction, BLISS will optically chop the signal at 5 Hz and will require each TES to have a response time below 30 ms. The instrument will be cooled using an adiabatic demagnetization refrigerator (ADR).

This year, the BLISS team made important steps toward achieving the required NEP by demonstrating operation of arrays of iridium (Ir) TESs (Tc=130 mK) with the SQUID MUX cooled to the operational temperature using an ADR. The measured system NEP is a world record for TES readout with a SQUID MUX.

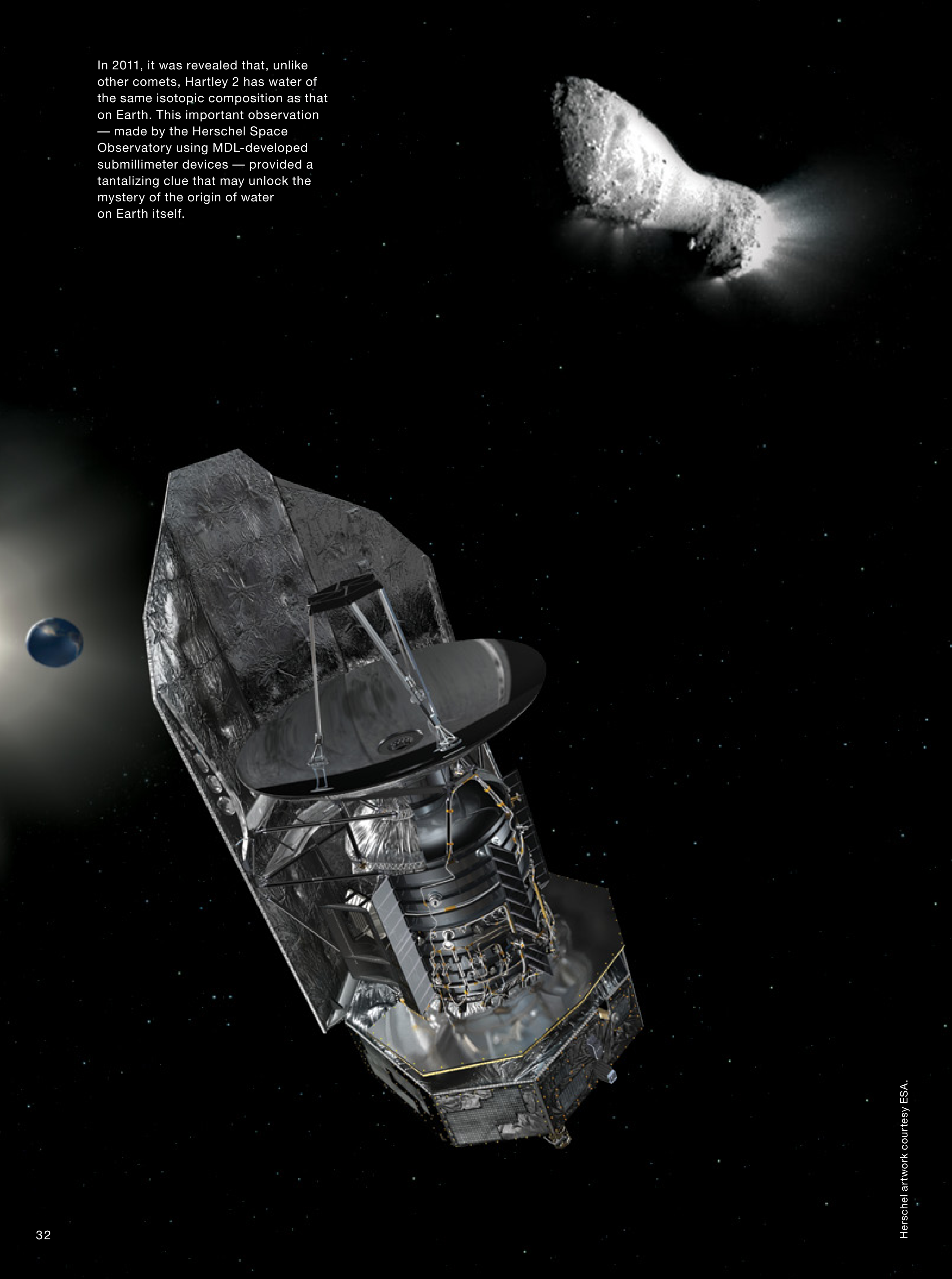




Right (top to bottom): Micrograph of a segment of a 1D array of TESs with suspended Si_xN_y absorbers. Each absorber is Δy = 300 μm wide by Δx = 2000 μm long and designed to mount into the longest-wavelength band of BLISS. Beam dimensions are 1000 μm long by 0.25 μm thick by 0.4 μm wide.

Best results to date were obtained from arrays of Ir TESs with T_C=130 mK. Two types of support beams for membrane-isolated TESs were investigated: straight and meander support beams. Each TES had four support beams with cross-section of 0.25 μm×0.4 μm. Straight beams were 1 mm long, while the meander beams were 2 mm long.

In 2011, it was revealed that, unlike other comets, Hartley 2 has water of the same isotopic composition as that on Earth. This important observation — made by the Herschel Space Observatory using MDL-developed submillimeter devices — provided a tantalizing clue that may unlock the mystery of the origin of water on Earth itself.



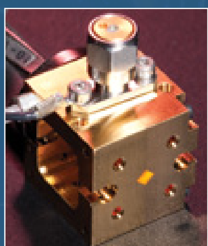
Herschel artwork courtesy ESA.

SUBMILLIMETER-WAVE ADVANCED TECHNOLOGIES

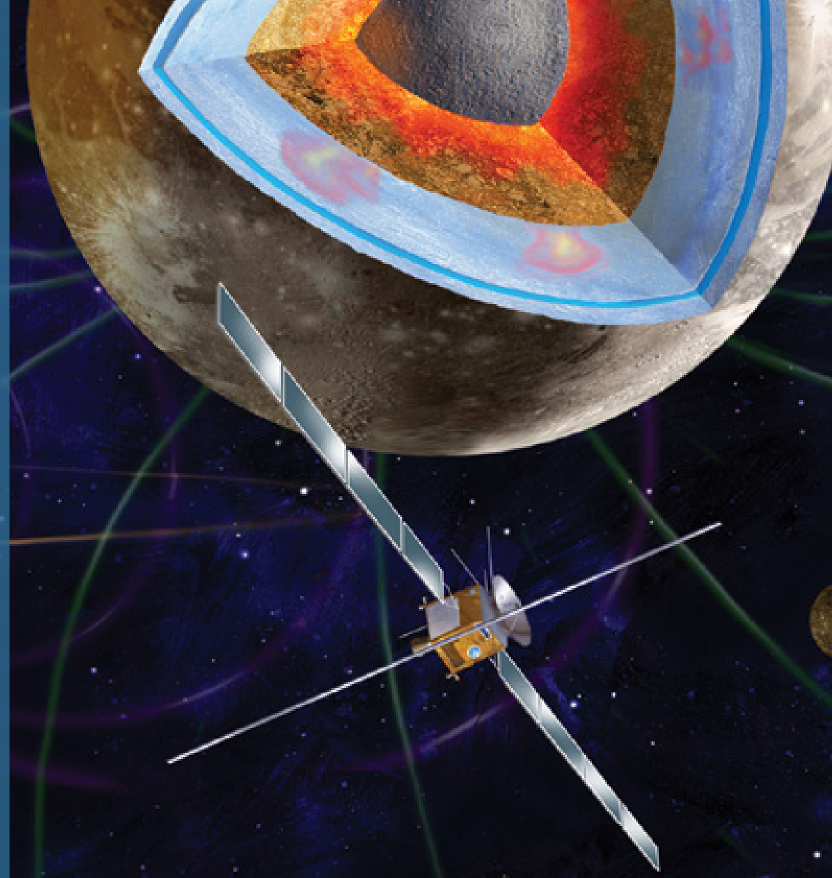
Our growing capabilities allow us to peer into the early universe, study comets to discover where Earth's water came from, keep us secure at airports with fast terahertz scanning, and ensure exciting future missions to Venus and the outer planets.

The Submillimeter-Wave Advanced Technology Group's focus is developing components and technologies to enable spaceborne instruments based on high-resolution heterodyne spectrometers for Earth remote sensing missions, planetary missions, and astrophysics observatories. The group's technical expertise is also utilized for ground-based applications spun off from heterodyne receiver technologies. Heterodyne technology allows mapping and detection of unique molecular signatures with very high spectral resolution over a wide range of wavelengths. JPL/NASA has been the traditional leader in this field owing to its wide applicability for astrophysics and Earth remote sensing. Next-generation technology development will allow us to build and deploy compact, submillimeter-wave receivers that are ideally suited for planetary missions. >>

Compact Submillimeter Spectrometers for Outer Planet Missions



Detection of water molecules in the universe is a long-standing goal of NASA planetary missions. Currently, MDL-produced devices are on board the MIRO (Microwave Instrument for the Rosetta Orbiter) instrument that recently rendezvoused with comet Lutetia. Advanced devices are being designed and fabricated at the MDL that would allow a proposed upcoming mission to the outer planets to fly a heterodyne receiver in the 500–600 GHz range that could quantitatively determine the presence of water molecules in the ppb range. This would be part of the proposed JUICE (Jupiter Icy Moon Explorer) mission. By combining several different custom chips in one block, the mass and volume of the receiver front-end can be reduced, making it more attractive for the long trip to the outer planets.



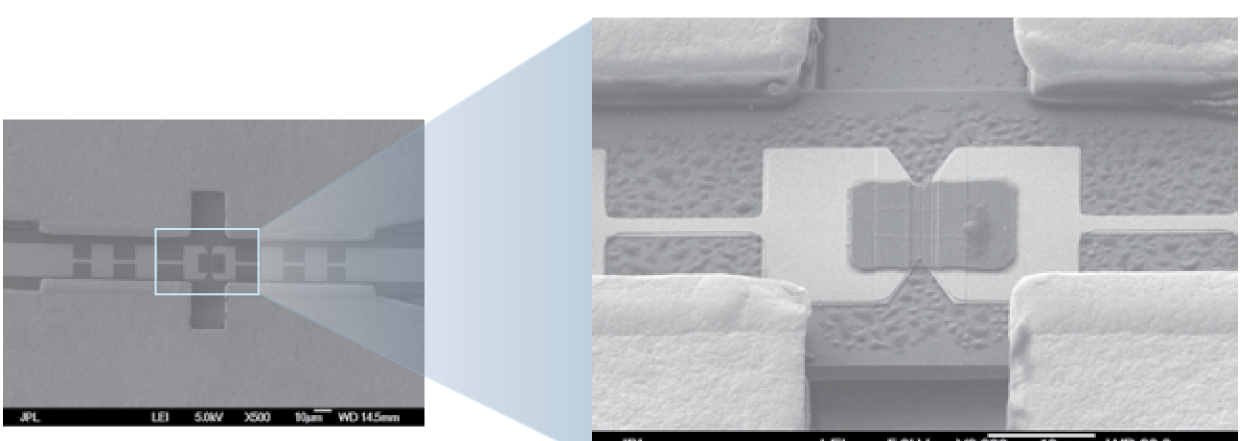
Above: Artist's impression of the Europa Jupiter System Mission, a proposed international mission to the Jupiter system.

Inset: A 500–600 GHz receiver front-end combines the local oscillator and mixer chips in a single block. It can be used to detect water molecules in the ppb range.

Artwork courtesy ESA/NASA.
Pre-decisional – for Planning and Discussion Purposes Only.

MDL-Fabricated Hot Electron Bolometers Establish Excellent Sensitivities in the THz range

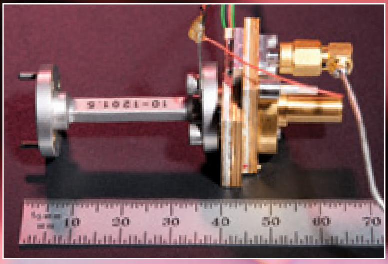
Hot electron bolometer (HEB)–based mixers enable detection of very faint signals, making them a valuable tool for astrophysics research. Engineers at MDL have fabricated and designed HEB mixers that have been successfully deployed in receiver systems. The receiver has a noise temperature of around 965 K at 2.74 THz. This establishes a new world record for sensitivity at this frequency. These receivers are being developed for long-duration balloon missions.



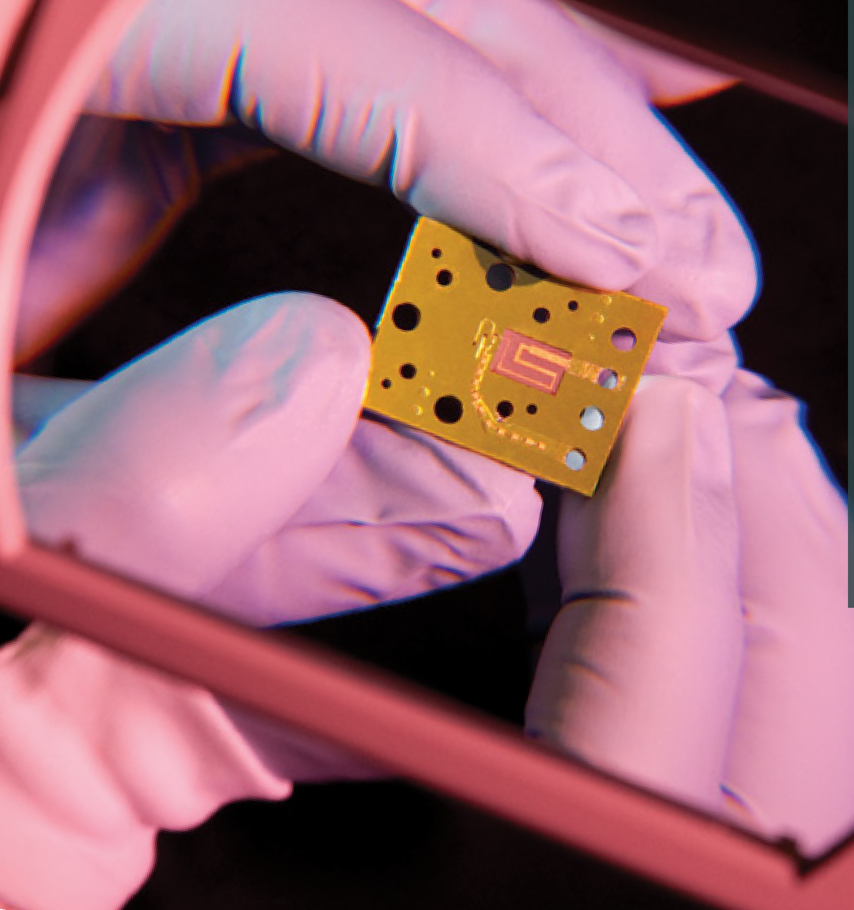
THz Imaging Radar Detects Concealed Weapons and Contraband at Long Standoff Ranges

Schottky diode–based mixer and multiplier devices have enabled us to build a 670-GHz imaging radar that can generate through-clothes imagery in about 1 second. A compact and robust instrument was built and delivered for field testing. The imaging rate of the instrument was increased by implementing several enhancements, including a new fast-scanning subreflector design, a faster but still low-noise chirp waveform generator, and faster analog-to-digital conversion and signal processing. Real-time through-clothes threat detection from 25-meter standoff ranges is now possible with frame rates of 1 Hz and spatial resolution of better than 1 cm.

Right: Through-clothes detection of a concealed weapon. A) A mock pipe bomb approximately 30 cm long. B) The mock bomb is then strapped to the torso, and C) concealed by a jacket. D) Through-clothes radar imagery reveals the concealed threat.



Left: A 600-GHz receiver front-end has been demonstrated that is built with the radiometer-on-a-chip technology (pictured below). This technology will allow us to make compact array receivers for future NASA missions.



Radiometer-On-A-Chip: A Roadmap for THz Array Receivers

A concerted effort is underway to develop technology that can allow us to build compact array receivers for future NASA missions. Utilizing MDL's world-class manufacturing capability, we developed a concept for making a radiometer-on-a-chip, making it possible to deploy compact array receivers in the future. Normally, the mixer and the multiplier chips are packaged in separate wave-guide blocks and then connected to form the receiver front-end. One way to make super-compact receiver front-ends is to etch the waveguide and channel cavities in silicon bulk material, and to integrate the power amplifiers, multiplier, and mixer chip in a single silicon micromachined block. A 600-GHz front-end has been demonstrated with this technology.

Delivering science instruments through sulfuric acid clouds to land on the hostile surface of Venus at 460 °C and 92 times the atmospheric pressure of Earth will require sensors and electronics capable of performing in extreme environments.
Read more about MDL developments on page 39.

Artist representation of a balloon concept for the Venus Flagship Mission Study.
Pre-decisional – for Planning and Discussion Purposes Only.

NANO AND MICRO SYSTEMS

Advances in nano- and micro-technologies drive development of electronics and sensors in our everyday lives, Earth and planetary exploration, industry, and defense.

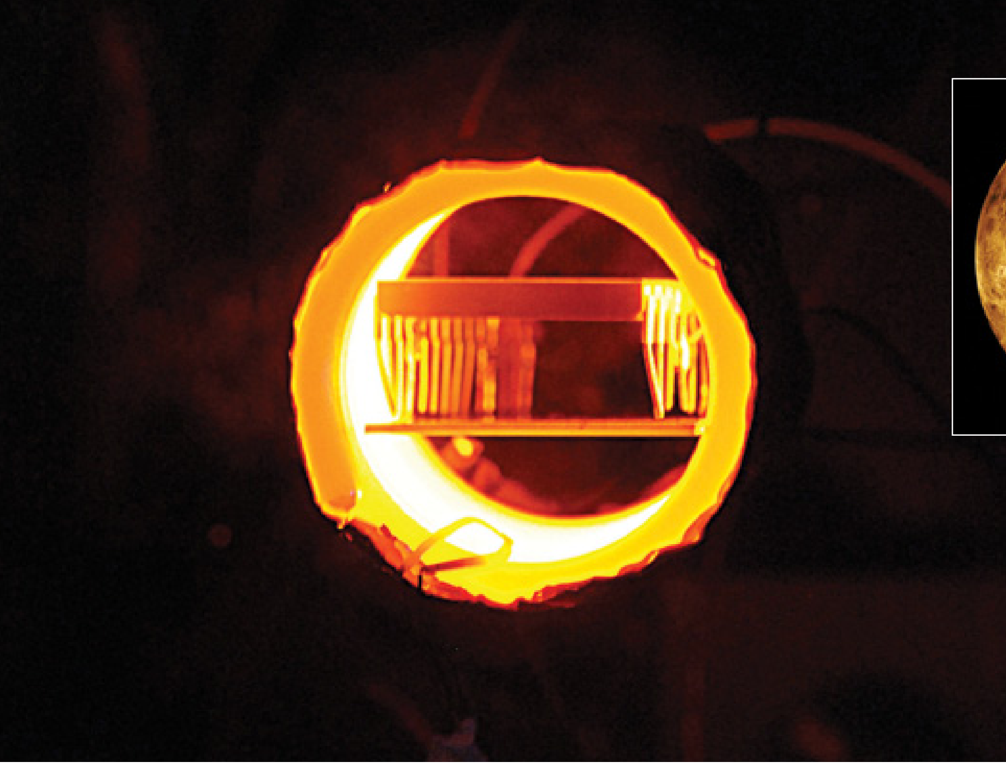
In 2011, the Nano and Micro Systems Group focused on miniature system development activities for various customers, including NASA, DoD, and commercial entities. The group is continuing development of the following technologies: sample verification sensors; gate-integrated, high-current-density, carbon nanotube field emission sources; and advanced miniature tools for stereo imaging for medical uses and planetary exploration. >>

Dr. Risaku Toda of MDL and Keith Patterson, a Caltech graduate student, test a first-generation membrane mirror actuator.

Collaborations to Develop Miniaturization Technologies for Space Exploration

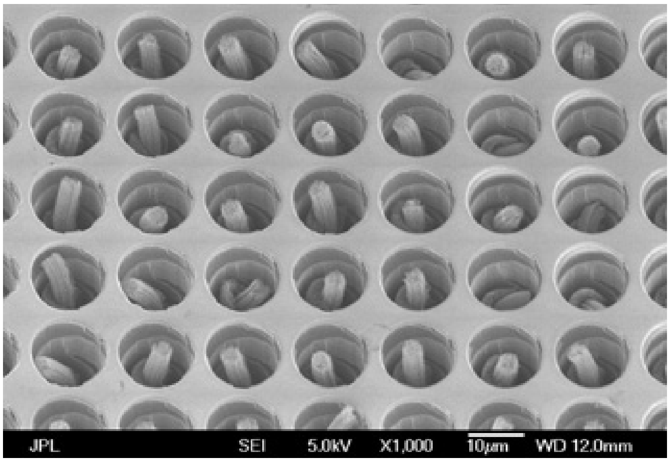
MDL is a participant in several collaborative technology development efforts for future space exploration. As part of an ongoing study by Caltech under the auspices of the Keck Institute of Space Studies, MDL and Caltech will develop a lightweight, deformable-membrane mirror technology for an in-space reconfigurable large-area telescope system. In addition, two new Defense Advanced Research Projects Agency (DARPA)–funded programs to develop precision microelectromechanical systems (MEMS) gyroscopes are in progress. The first is a collaborative effort with UC Irvine to build 3D-micromachined rate integrating gyroscopes; such devices would have infinite bandwidth. The second is a JPL-led project to design and build a miniature inertial measurement unit with an integrated clock. Both efforts leverage pioneering work on increased-sensitivity resonant vibratory MEMS sensors through construction from intrinsically high-quality-factor materials. NASA applications for these technologies include inertial navigation of miniature spacecraft, precision pointing of spacecraft instruments, and control during the critical entry, descent, and landing phase of lander missions.

Above: Artist's rendering of an autonomously assembling reconfigurable space telescope as conceived by Caltech.



Left: A carbon nanotube vacuum microelectronic device is being operated at high temperature inside a coil. This technology has the potential for applications for extreme environments such as Venus (pictured above).

Carbon Nanotube–Based Extreme Environment Vacuum Microelectronics



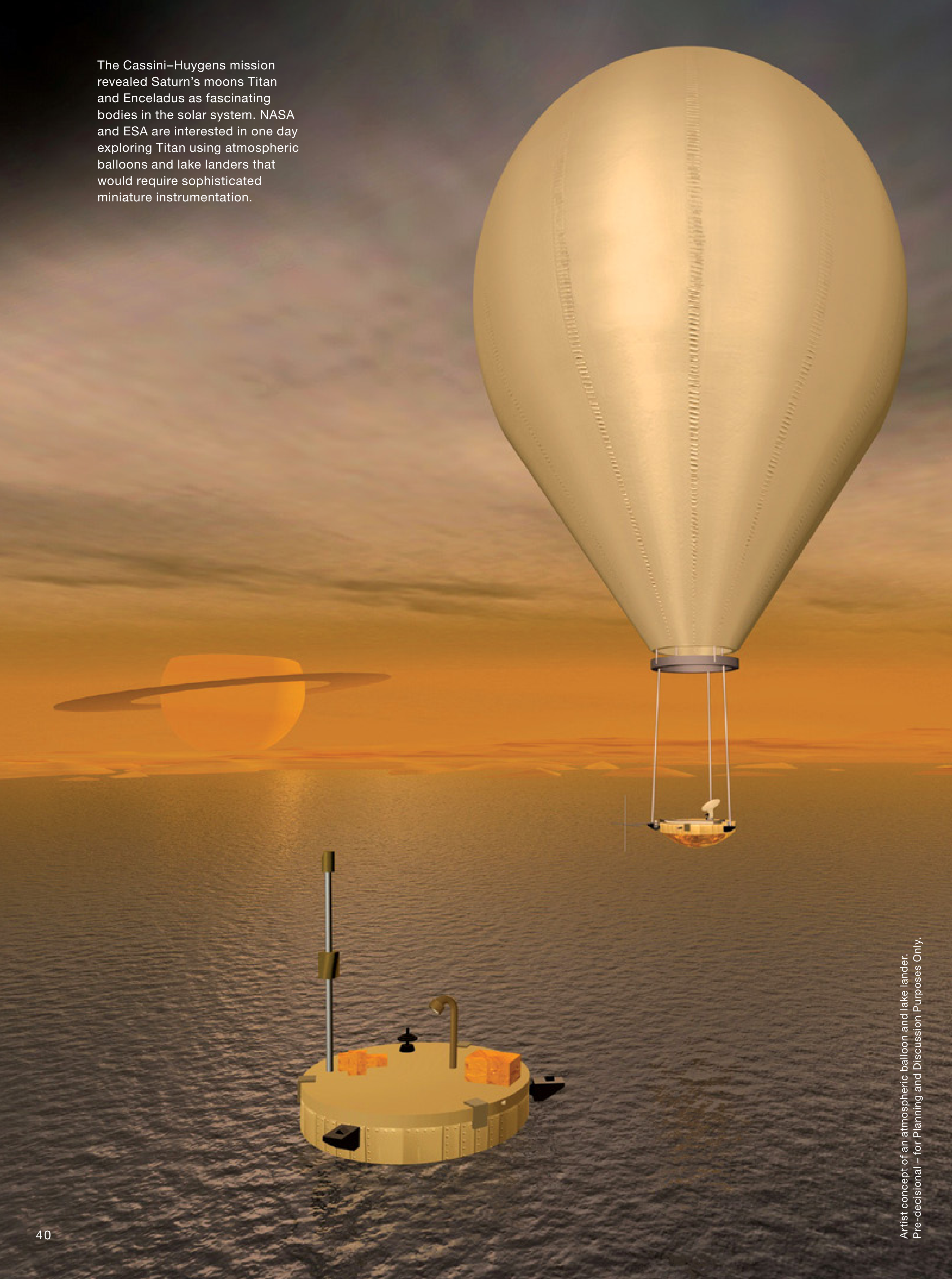
Carbon nanotube emitters integrated with extraction gate electrodes using a MDL-developed process.

Field emission from carbon nanotube (CNT) bundles has been applied to develop a new class of vacuum microelectronics for harsh environment applications. CNTs have demonstrated superior field emission performance because of their low emission threshold and high current density, and are compatible for monolithic integration with silicon structures to develop microelectronic/microsensor systems. This technology is applicable to in situ sensor electronics for applications where the operating environment is high-temperature and high-pressure, and has corrosive chemicals.

The digital and analog electronic devices developed using CNT-vacuum microelectronic technology can be integrated with sensor systems to achieve prolonged stand-alone operation during exploration. High-performance cold cathodes using arrays of CNT bundles have exhibited robust operation in poor vacuums of 10^{-5} to 10^{-6} Torr, a typically achievable range inside hermetically sealed microcavities. By monolithically integrating CNT cathodes with micromachined Si multigate structures, MDL has demonstrated a new class of programmable “vacuum” logic gates and achieved switching operation at temperatures up to 700 °C. Work is ongoing to improve design and achieve vacuum packaging to make stand-alone devices for circuit board integration.

CNT-vacuum microelectronics opens up a new regime of in situ electronics for novel sensor/electronics systems because of their inherent high-temperature tolerance and corrosion resistance. Unlike traditional vacuum tubes, these are low-power, miniature, and potentially as fast as their solid-state counterparts while exhibiting superior reverse bias or leakage current characteristics. MDL’s research on extreme environment sensors and electronics knowledge has the potential for multiple applications ranging from commercial oil and gas exploration to studies on Venus.

The Cassini–Huygens mission revealed Saturn's moons Titan and Enceladus as fascinating bodies in the solar system. NASA and ESA are interested in one day exploring Titan using atmospheric balloons and lake landers that would require sophisticated miniature instrumentation.



Artist concept of an atmospheric balloon and lake lander.
Pre-decisional – for Planning and Discussion Purposes Only.

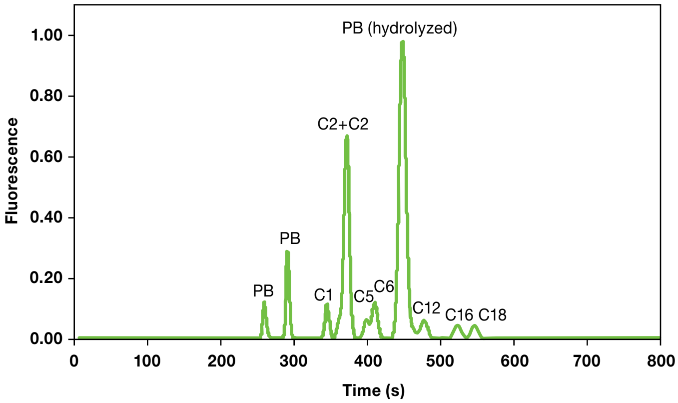
MICROFLUIDICS

Lab-on-a-chip innovations capable of analyzing complex organics will integrate our natural and technological world through liquid-based technologies of the future.

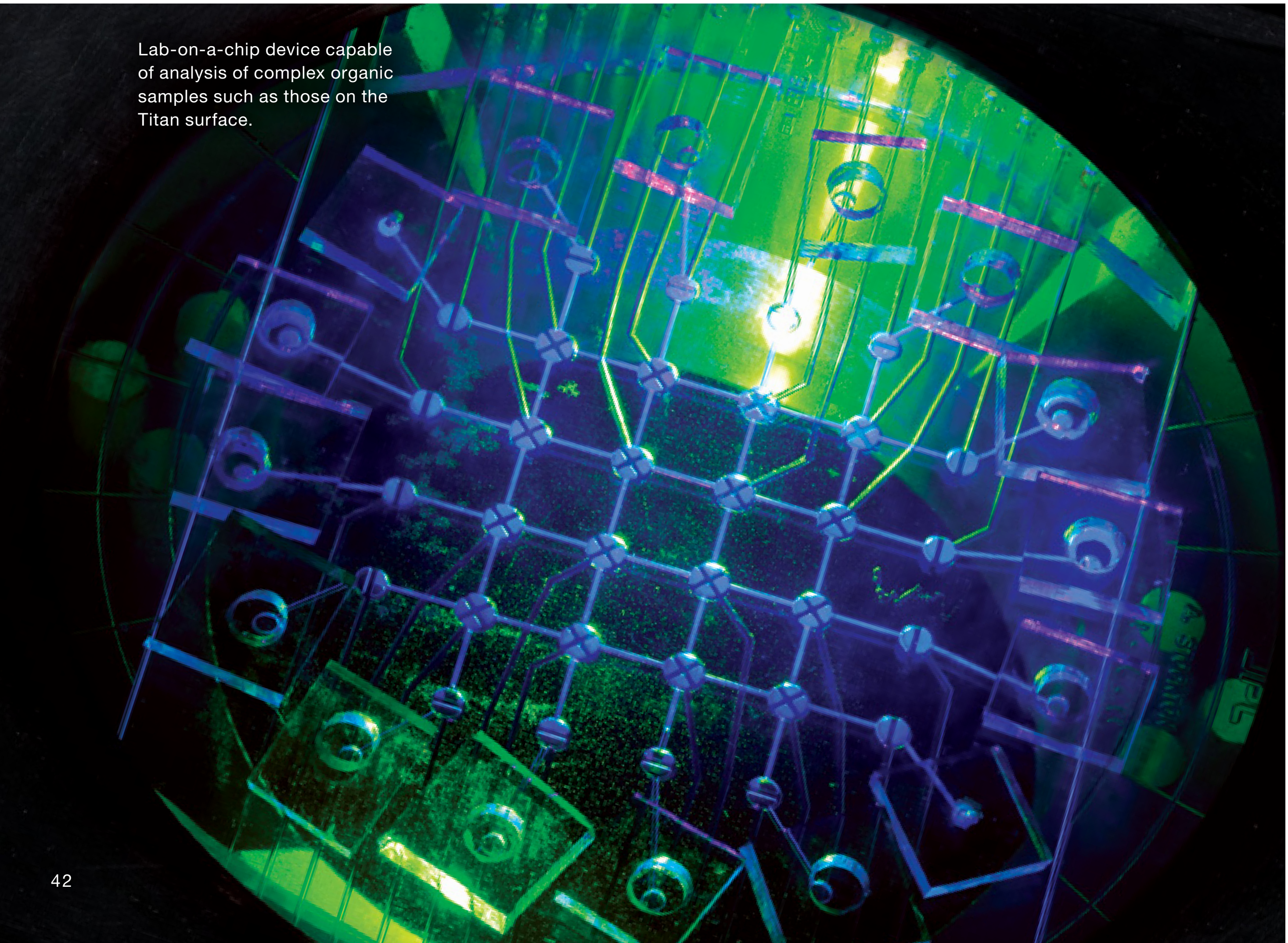
As planetary science evolved from the successful observational missions of the 70s, 80s, and 90s, there has been increased emphasis on the surface exploration of nearby accessible planets, resulting in the development and deployment of new physical, chemical, and geological instruments on robotic platforms. The work at MDL is focused on the development of the next generation of miniaturized lab-on-a-chip systems that can perform chemical analyses without needing a human operator during the process. Such technology is essential to NASA's search for habitable environments, prebiotic chemical syntheses, and extraterrestrial life in the solar system. >>

Lab-On-A-Chip and in the Freezer: Analyzing Titan's Organic Soup

Titan, Saturn's largest moon, is a captivating world with a thick atmosphere and an active "hydrological" cycle. On this frigid moon, the liquid phase is not water but hydrocarbons — methane and ethane — which form clouds, rain, and large lakes. Energetic atmospheric chemistry generates a plethora of complex organic molecules, which form aerosols and settle onto the surface. Although it is unclear how much organic material is dissolved in the hydrocarbon lakes, the shorelines and extended planetary dune structures are thought to hold vast reserves of complex organics waiting to be explored. Analysis of these complex mixtures requires versatile instrumentation, and in our laboratory we are developing new technologies to enable such analyses. Using tholins, simulated Titan organic material, we have demonstrated automated lab-on-a-chip devices such as that pictured below. In our work, we utilize solvents with low freezing points that can dissolve organics and enable in situ analyses in Titan's native environment. By coupling low-temperature-capable architectures with ultrasensitive detection techniques, we can generate a "fingerprint" of a complex organic sample, such as long-chain amines in the figure above, to better understand the organic chemistry on Titan.

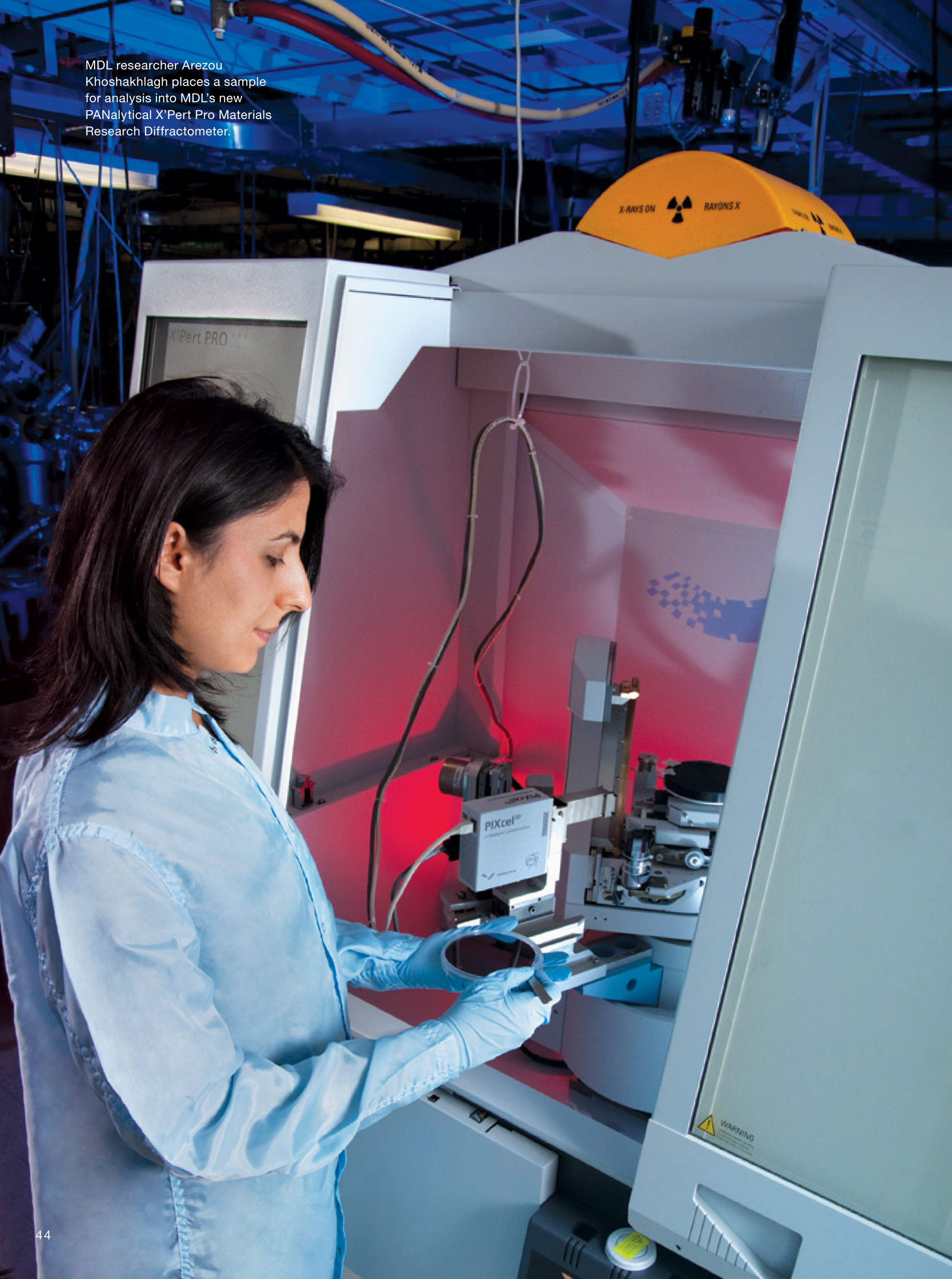


Analysis of a mixture of organic compounds, specifically amines with different carbon chain lengths (C1 to C18). They are dissolved in ethanol and detected on a lab-on-a-chip device. PB is Pacific Blue, the dye that attaches to the amines and makes them fluorescent.



Lab-on-a-chip device capable of analysis of complex organic samples such as those on the Titan surface.

NASA postdoctoral fellow Dr. Amanda Stockton tests the novel autonomous 32-valve microfluidic processor fabricated at MDL. Its enhanced reprogrammability and processing power would enable complex chemical analyses to be performed in situ on extraterrestrial targets like Titan.



MDL researcher Arezou Khoshakhlagh places a sample for analysis into MDL's new PANalytical X'Pert Pro Materials Research Diffractometer.

INFRASTRUCTURE

The foundation of our technical implementation and innovation relies on sophisticated new instrumentation in ultraclean, safe environments.

The sophisticated semiconductor processing that takes place in the MDL requires complex integrated building systems. Oversight and local configuration control is provided by the Central Processing and MDL Support Group, which also maintains a staff for specialized processing support. We manage, coordinate, and provide direct services in maintaining the building infrastructure and equipment, including life safety systems for safety assurance. >>

Investment and Infrastructure Improvements

In MDL's continuing story of growth and renewal, a number of significant investments and infrastructure improvements were made in 2011, with emphasis on updating safety and characterization capabilities.

Infrastructure Improvements

1. Eleven local evacuation zones vs. a single global evacuation zone were established for oxygen deficiency alarms.

2. New capabilities were added to MDL's toxic and combustible gas monitoring systems. Specific additions include two NF3 detectors (a new detection capability required for in situ sample preparation for the Veeco GEN200 Si MBE), spare major components for the Vertex Toxic Gas Monitoring System (to minimize downtimes in the event of a failure), and an updated portable combustible gas detector (to investigate leaks).

3. MDL's Incipient Fire Detection system was updated and coverage points were expanded, providing enhanced fire detection coverage

Equipment Investments/Upgrades

1. X-ray Diffraction System: PANalytical X'Pert Pro Materials Research Diffractometer (MRD) with High-Temperature Domed Hot Stage. This system replaced an older capability and provides important enhanced characterization capabilities for MDL. The system has a heated stage that can go up to 1100 °C. It is capable of handling up to 8-inch-diameter wafers and can do automated wafer mapping, including rocking curves and reciprocal space

MDL Safety Engineer, Michael Martinez, monitors the status on MDL's updated Incipient Fire Detection System.

JPL Sends Miniaturized Names and Messages from the Public to Mars

As part of its outreach efforts, JPL received over 1.2 million names and signatures from 246 countries around the world to be sent to Mars on board the Curiosity Rover. Over 1,300 pages were miniaturized and duplicated by MDL's e-beam lithography on 2 chips. The width of each page was miniaturized to approximately the width of a human hair. Also miniaturized and included were the Leonardo Da Vinci Codex on Bird Flight, the Leonardo Da Vinci Self Portrait, letters from the JPL Director and Project Managers, a portrait and memorial to project manager John Klein (d. May, 2011), and student essays and wishes. The 2 chips were packaged and mounted on the body of the Mars Science Laboratory (MSL) rover "Curiosity" which was successfully launched on November 26, 2011, and is being delivered to the surface of Mars.

Above: SEM Micrographs of some of the over 1.2 million names and signatures and a message from the JPL director and President of Caltech contained on the two chips fabricated and packaged in MDL (pictured). The chips were attached to the MSL rover for delivery to the surface of Mars as part of NASA/JPL's outreach activities.

maps for epitaxy. In addition, the system has the ability to do powder measurements and phase ID to establish unknown residues on wafers. It is also capable of doing grazing incident measurements and reflectometry, which enables thin-film measurements for amorphous, noncrystalline films and multilayers establishing not only film thicknesses, but also measurements of texture, density, stress, crystal size in polycrystalline films, and roughness.

2. Nanometrics Electrochemical Capacitance Voltage ECV Pro Profiler: This system provides precise etching capabilities for characterization and enables the measurement of carrier type and concentration vs. sample depths (doping profiles) with 1 nm depth resolution. It may be utilized on films of III-V semiconductors, II-VI semiconductors, III-Nitrides, Si, and SiC.

MDL researcher, Alexander Soibel, reviews characterization data on the screen of MDL's new ECV Pro Profiler.

3. Ion Gun for the Veeco E-beam Evaporator allowing in situ sample surface cleaning and preparation.

4. General use computers (qtn.=4) were replaced in the MDL cleanrooms with updated units and operating systems.

Significant participation in outreach activities was also accomplished in 2011: 12,279 members of the public toured the MDL facility at the JPL Open House (May 14–15, 2011), and more than five tours per month were given to specific individuals or groups during the year.

Appendix A — MDL Equipment Complement

Material Deposition

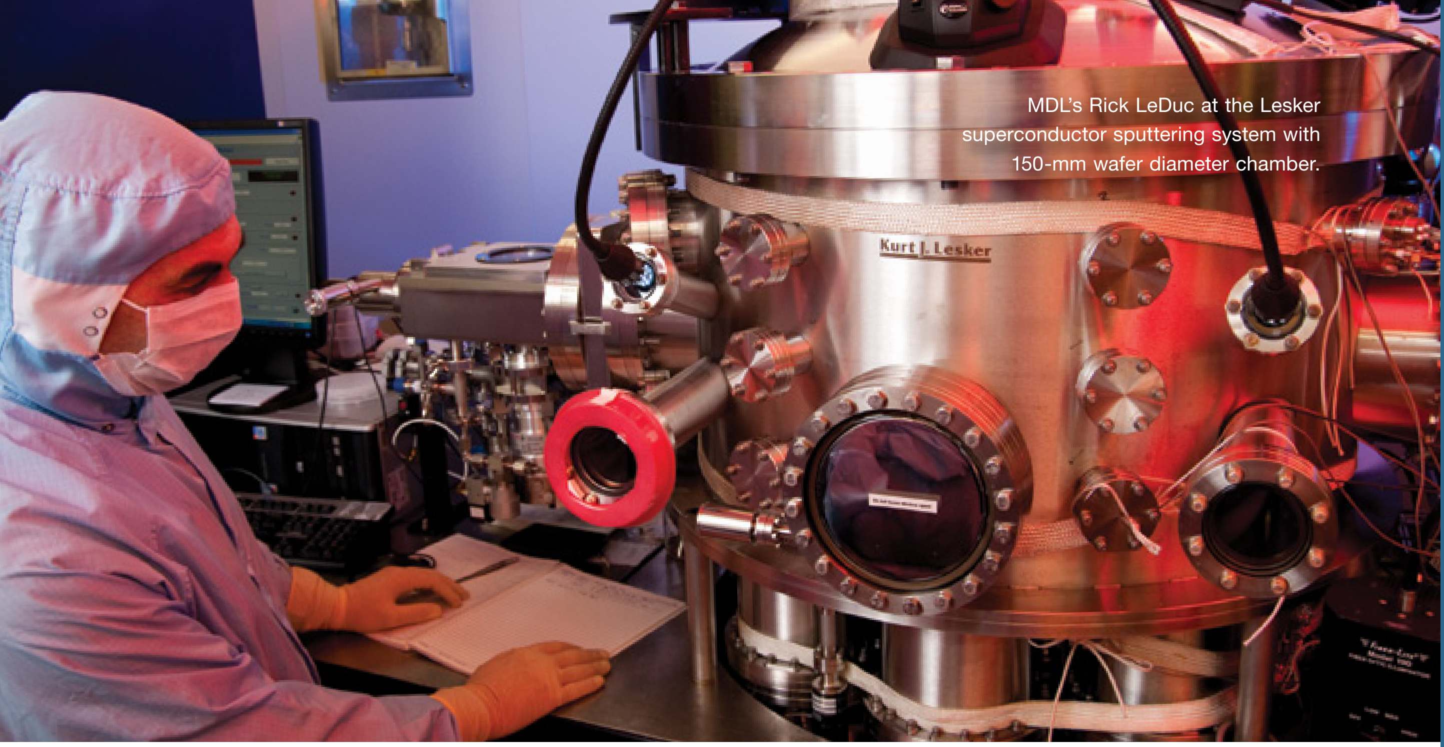
- Thermal Evaporators (6)
- Electron-Beam Evaporators (7)
- Ultra-High-Vacuum (UHV) Sputtering Systems for Dielectrics and Metals (3)
- Ultra-High-Vacuum (UHV) Sputtering Systems for Superconducting Materials (2)
- AJA Load-Locked Thermal Co-Evaporator for Broadband IR Bolometer Depositions
- Plasma-Enhanced Chemical Vapor Deposition (PECVD) System for Doped and Undoped Amorphous Silicon
- Plasmatherm 790 Plasma-Enhanced Chemical Vapor Deposition (PECVD) System for Dielectrics
- Oxford Plasmalab System 100 Advanced Inductively Coupled Plasma (ICP) 380 High-Density Plasma-Enhanced Chemical Vapor Deposition (HD PECVD) System for Low-Temperature Dielectric Growths
- Oxford Plasmalab 80 OpAL Atomic Layer Deposition (ALD) System with Radical Enhanced Upgrade
- Low-Pressure Chemical Vapor Deposition (LPCVD) TYSTAR Systems with 6 Tubes for
  - Low-Stress Silicon Nitride (2)
  - Low-Temperature Oxide — Silicon Dioxide
  - Doped and Undoped Polysilicon
  - Wet Pyrogenic Oxidation
  - Steam Oxidation
- Carbon Nanotube Furnace Systems (2)
- Electroplating Capabilities
- Molecular-Beam Epitaxy (MBE)
  - Veeco GEN200 (8-inch) Si MBE for UV CCD Delta Doping (Silicon)
  - Veeco Epi GEN III MBE (Antimonide Materials)
  - Riber MBE for UV CCD Delta Doping (Silicon)
  - Riber Device MBE (GaAs)
- Thomas Swann Metallo-Organic Chemical Vapor Deposition (MOCVD) System

Lithographic Patterning

- Electron-Beam (E-beam) Lithography: JEOL JBX9300FS E-beam lithography system with a 4 nm spot size, 100,000 volt acceleration voltage, ability to handle wafers up to 12 inches in diameter, and hardware and software modifications to deal with curved substrates having up to 3 mm of sag
- GCA Mann Wafer Stepper with custom stage allowing different sizes and thicknesses of wafers (0.7 µm resolution)
- Canon EX3 Stepper with EX4 Optics (0.25 µm resolution)
- Contact Aligners:
  - Karl Suss MJB3
  - Karl Suss MJB3 with backside IR
  - Suss MA-6 (UV300)
  - Suss BA-6 (UV400) with jigging supporting Suss bonder
- Wafer Track/Resist/Developer Dispense Systems:
  - Suss Gamma 4 Module Cluster System
  - Site Services Spin Developer System
- Yield Engineering System (YES) Reversal Oven
- Ovens, Hotplates, and Manual Spinners

Dry Etching

- Commonwealth IBE-80 Ion Mill
- Branson Plasma Ashers
- Tepla PP300SA Microwave Plasma Asher



MDL's Rick LeDuc at the Lesker superconductor sputtering system with 150-mm wafer diameter chamber.

Fluorine-based Plasma Etching Systems

- STS Deep Trench Reactive Ion Etcher (DRIE) with SOI Upgrade
- Unaxis Shuttleline Load-Locked Fluorine ICP RIE
- Plasmaster RME-1200 Fluorine RIE
- Plasma Tech Fluorine RIE
- STJ RIE for Superconductors
- Custom XeF2 etcher

Chlorine-based Plasma Etching Systems

- Unaxis Shuttleline Load-Locked Chlorine ICP RIE
- Plasmaster RME-1200 Chlorine RIE
- ECR 770 Chlorine RIE
- Oxford Inductively Coupled Plasma (ICP) Chlorine RIE

Wet Etching and Sample Preparation

- RCA Acid Wet Bench for 6-inch Wafers
- Solvent Wet Processing Benches (7)
- Rinser/Dryers for Masks and Wafers
- Chemical Hoods (7)
- Acid Wet Processing Benches (8)
- Critical Point Dryer
- Rapid Thermal Processors/Contact Alloyers (2)
- Polishing and Planarization Stations (5)
- Strasbaugh 6EC Chemical Mechanical Polisher

Packaging

- SET FC-300 Flip-Chip Bump Bonder
- Karl Suss Wafer Bonder
- Electronic Visions Wafer Bonder
- Research Devices Bump Bonder (High Pressure)
- Fynetech Fineplacer 96 "Lambda" Bump Bonder
- Thinning Station and Inspection Systems for CCD Thinning
- Wire Bonding
- DISCO 320 and 321 Wafer Dicers (2)
- Tempress Scriber
- Pick and Place Blue Tape Dispenser System
- Loomis LSD-100 Scriber Breaker

Characterization

- Profilometers (2)
- FSM 128 Film Stress Measuring System
- Leitz Interferometer
- Sentech SE 850 Multispectral Ellipsometer
- Dimension 5000 Atomic Force Microscope (AFM) with Large Sample Stage
- KLA-Tencor Surfscan 6220 Wafer Particle Monitor
- JEOL JSM-6700 Field Emission SEM with EDX
- Nikon Inspection Microscope with Image Capture
- Confocal Microscopes
- Electrical Probe Stations with Parameter Analyzers (3)
- Photoluminescence Mapping System
- Fourier Transform Infrared (FTIR) Spectroscopy
- PANalytical X'Pert Pro MRD with DHS High-Temperature Stage X-ray Diffraction System
- Surface Science SSX501 X-ray Photoelectron Spectrometer (XPS) with Thermal Stage
- Custom Ballistic Electron Emission Microscopy (BEEM) System
- Custom UHV Scanning Tunneling Microscope (STM)
- Nanometrics ECV Pro Profiler

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New Technology Reports (NTRs)

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Patents

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Space Act Awards

The Space Act Awards program was authorized under the Space Act of 1958 to provide official recognition and to grant equitable monetary awards for those inventions and other scientific and technical contributions that have helped to achieve NASA's aeronautical and space goals. The awards are also designed to stimulate and encourage the creation and reporting of similar contributions in the future.

1. Space Act Award: Real-Time Monitoring of Indium Bump Reflow and Oxide Removal Enabling Optimization of Indium Bump Morphology, F. Greer, M. Hoenk, M.Dickie, T. Jones, T. Cunningham, E. Blaze, and S. Nikzad.

2. Space Act Award: Multi-Angle and Rear Viewing Laparoscopic Endoscope (MARVEL), S. Y. Bae, A. Liao, H. R. Shahinian, and H. Manohara.

3. Space Act Award: Development of Heterojunction Infrared Detectors, S. Gunapala, D. Ting, and C. Hill.

Other Awards and Distinguished Recognition

1. NASA Exceptional Service Medal: For exceptional service and operation of the Microdevices Laboratory that has produced state-of-the-art technology and flight components enabling NASA science instruments, James L. Lamb.

2. JPL Group Achievement Award: Creative development of mid-infrared focal plane array technology, David Ting, Arezou Khoshakhlagh, Alexander Soibel, Sam Keo, John Liu, Frank Greer, Ranty Liang, Jean Nguyen, Jason Mumolo, and Sir Rafol.

3. IEEE Distinguished Lecturer Award: Sarath Gunapala.

4. JPL Magellan Award: Leadership in the Development of Infrared Technology, Sarath Gunapala.

5. JPL's Senior Research Scientists (SRS) selected Doug Bell to serve on JPL's Senior Research Scientist Council (SRSC).

6. IEEE Women in Engineering (WIE) selected Shouleh Nikzad as a role model and pioneer engineer.

7. Technical Achievement Award — US Army RDECOM-CERDEC (Research, Development and Engineering Command-Communications-Electronics Research, Development, and Engineering Center): For exceptional scientific and technical contributions which have been determined to be of significant value in the advancement of the mid-wavelength infrared detector technology, David Ting.

8. Group Achievement Award — US Army RDECOM-CERDEC: For exceptional scientific and technical contributions which have been determined to be of significant value in the advancement of the infrared focal plane array technology, David Ting, Arezou Khoshakhlagh, Alexander Soibel, Sam Keo, John Liu, Frank Greer, Ranty Liang, Jason Mumolo, Sir Rafol, Jean Nguyen, and Sarath Gunapala.

9. Career Achievement Award — US Army RDECOM-CERDEC: For exceptional scientific and technical contributions which have been determined to be of significant value in the advancement of the infrared detector technology, entitled: Infrared Detector and Focal Plane Array Technologies Based on III-V Semiconductors, Sarath Gunapala.

10. 2011 Edward Stone Award: For Outstanding Research Publication, "Developing a new method for capturing high-temporal-resolution laser Raman spectroscopy," Jordana Blacksberg.

All work described in this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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JPL 400-1471 02/12